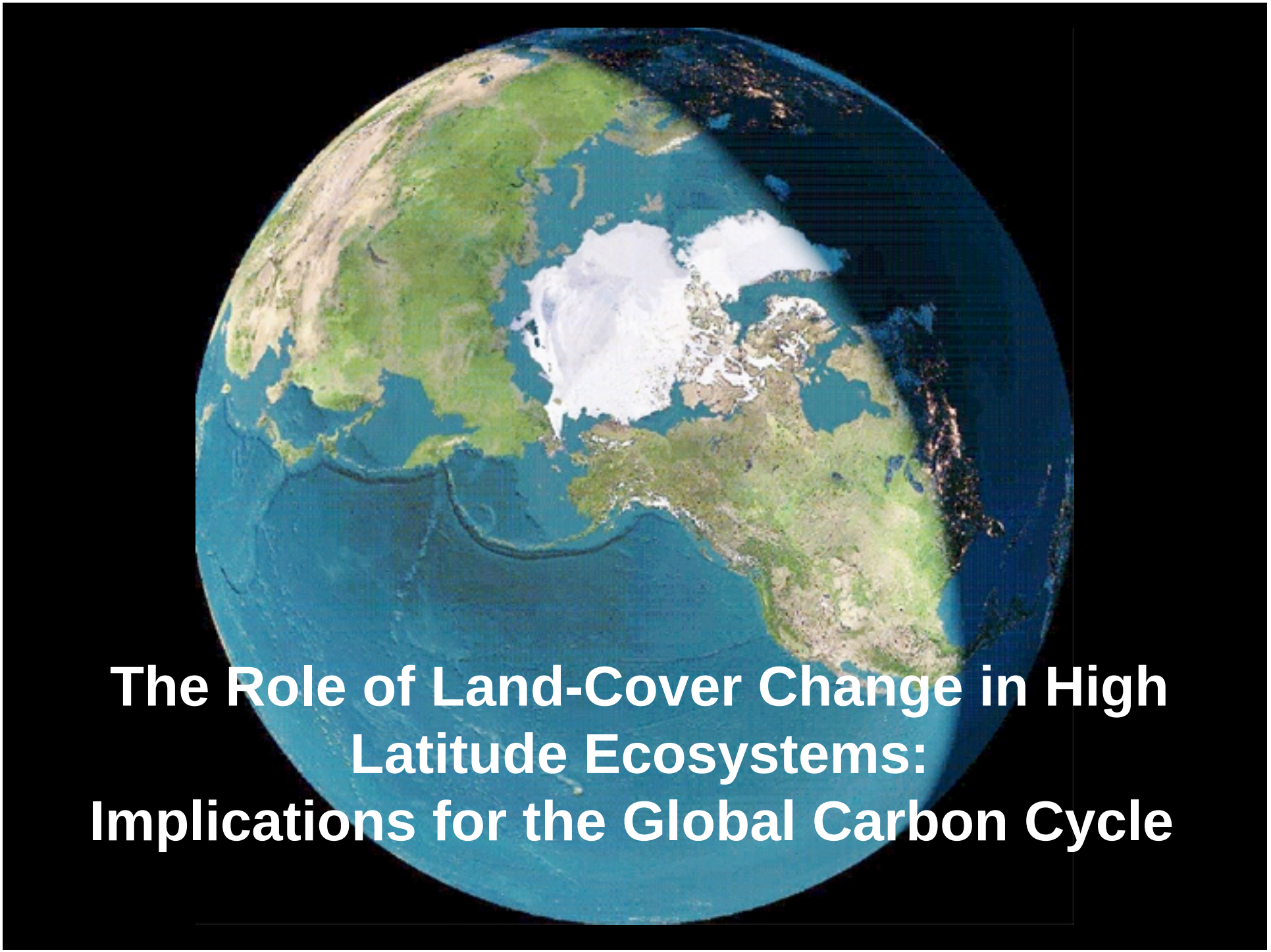
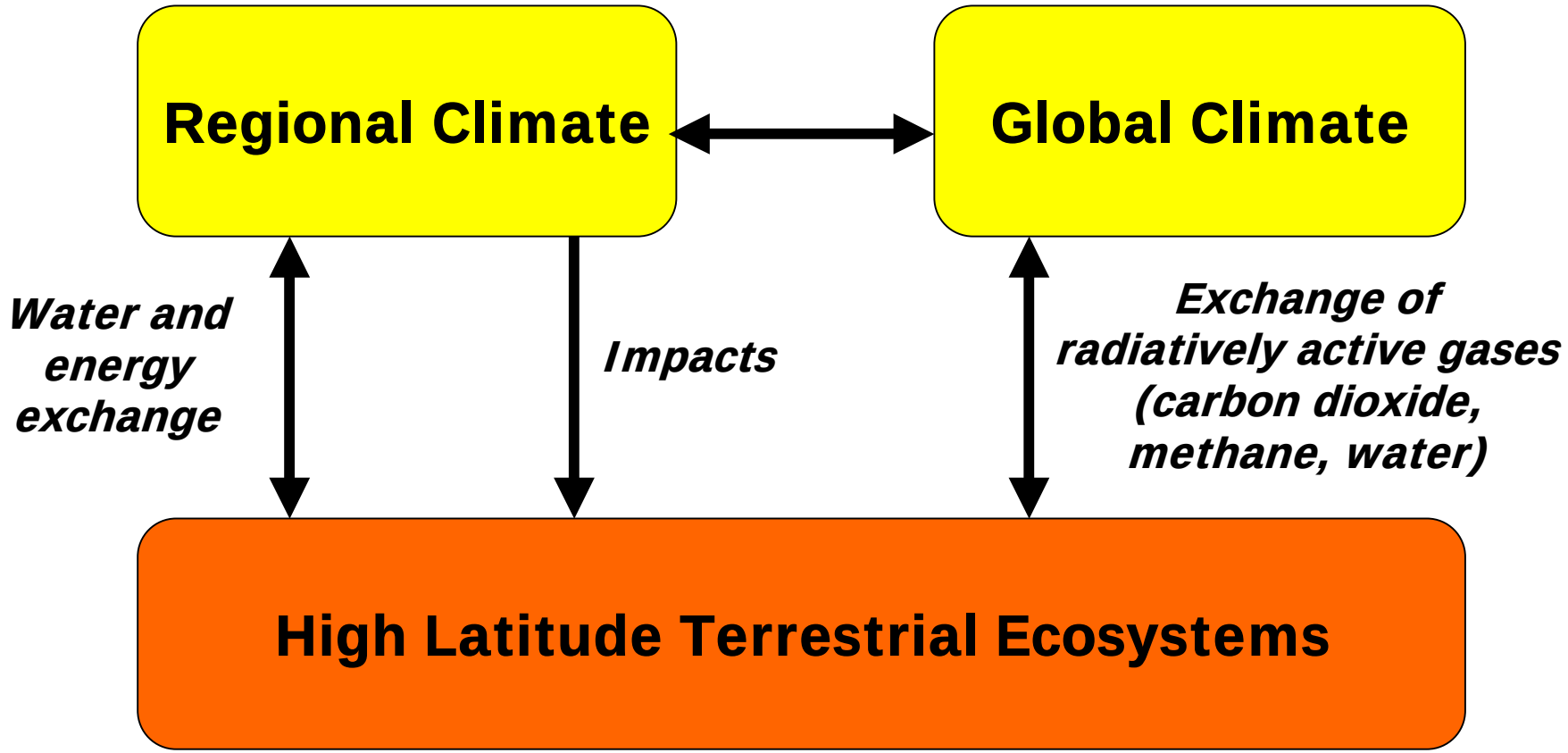


The Role of Land-Cover Change in High Latitude Ecosystems: Implications for the Global Carbon Cycle

Global Change in High Latitude Ecosystems



Participants

- A. David McGuire (PI, UAF)
- Dave Verbyla (Co-PI, UAF)
- Jerry Melillo (Co-PI, MBL)
- Rose Meier (UAF)
- Dave Kicklighter (MBL)
- Matt Macander, Cherie Silapaswan, Aaron Woods, Qianlai Zhuang, Dorte Dissing
- Scott Rupp, Terry Chapin, Tony Starfield

Project Goals

- **Develop prototype spatially explicit modeling framework to elucidate how land-cover change in high latitude ecosystems influences carbon storage**

- **Apply modeling framework to assess sensitivity and uncertainty of terrestrial carbon storage responses in high latitude ecosystems**
  - **Historical responses**
  - **Future responses**

Strategy

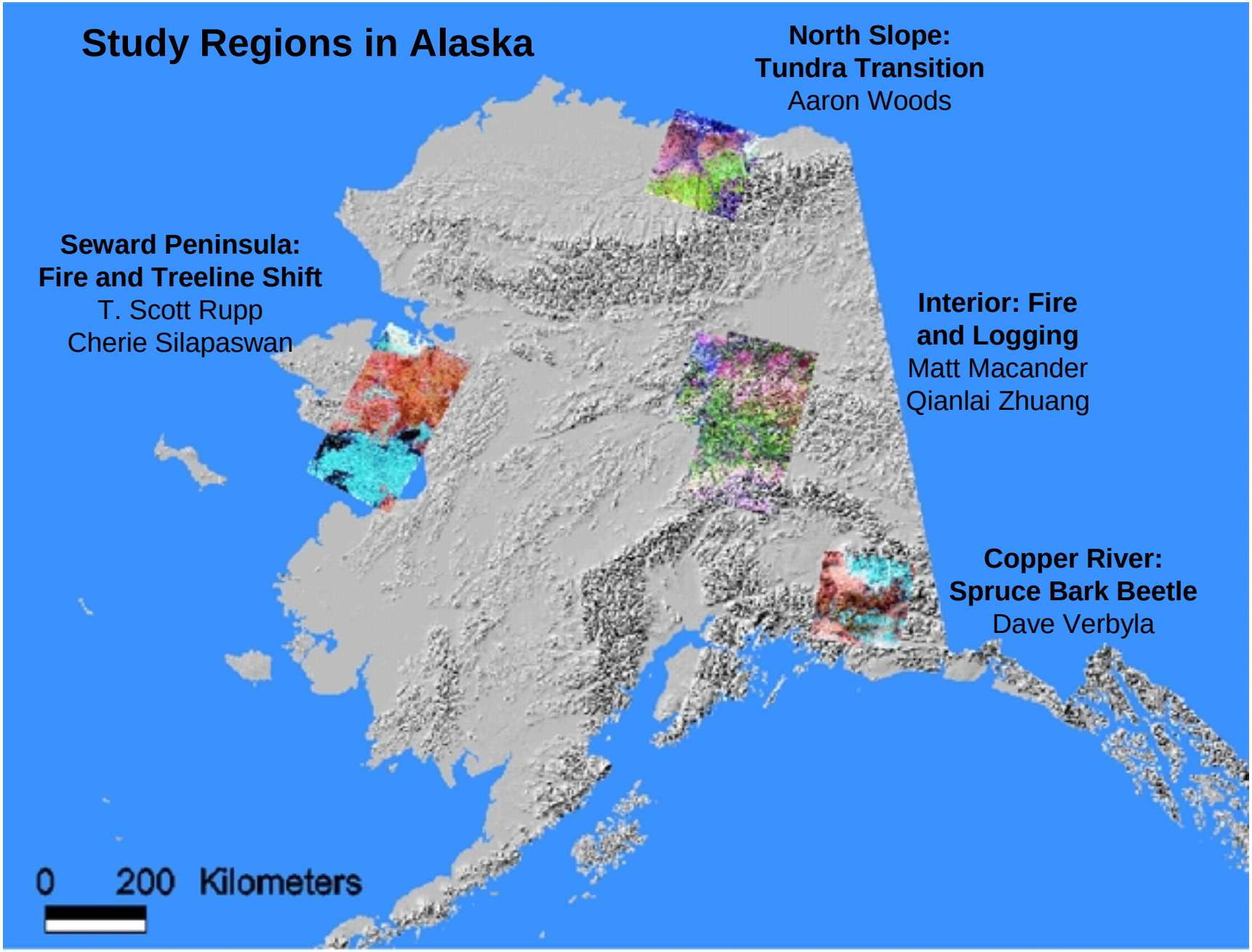
- **Focus on Alaska**
- **Develop historical transient land cover**
- **Develop components of modeling framework**
- **Application of modeling framework**
  - **Retrospective analyses**
  - **Prognostic analyses**

Why Alaska?

- **Substantial development over last 30 years**
- **Timing and extent of disturbances known**
- **Major disturbances include fire, logging, and insect infestation**
- **Vegetation replacement may be occurring**
- **Climate change may be affecting vegetation dynamics and the frequency and extent of disturbances**
- **Process-based research (taiga/tundra LTERs)**

Development of Transient Land Cover

- **Focus: 4 regions in Alaska plus Global**
  - **Tanana River Valley - fire and logging**
  - **Copper River Valley - insects and logging**
  - **Seward Peninsula - vegetation dynamics and fire**
  - **North Slope - vegetation dynamics**
  - **Global - agricultural land use**
- **Change detection**
  - **Aerial Photography**
  - **Landsat MSS, TM**
  - **AVHRR**
  - **Ancillary Data Sets**


Study Regions in Alaska
North Slope:
Tundra Transition
Aaron Woods
Seward Peninsula:
Fire and Treeline Shift
T. Scott Rupp
Cherie Silapaswan
Interior: Fire
and Logging
Matt Macander
Qianlai Zhuang
Copper River:
Spruce Bark Beetle
Dave Verbyla
0 200 Kilometers

Change Detection in Interior Alaska

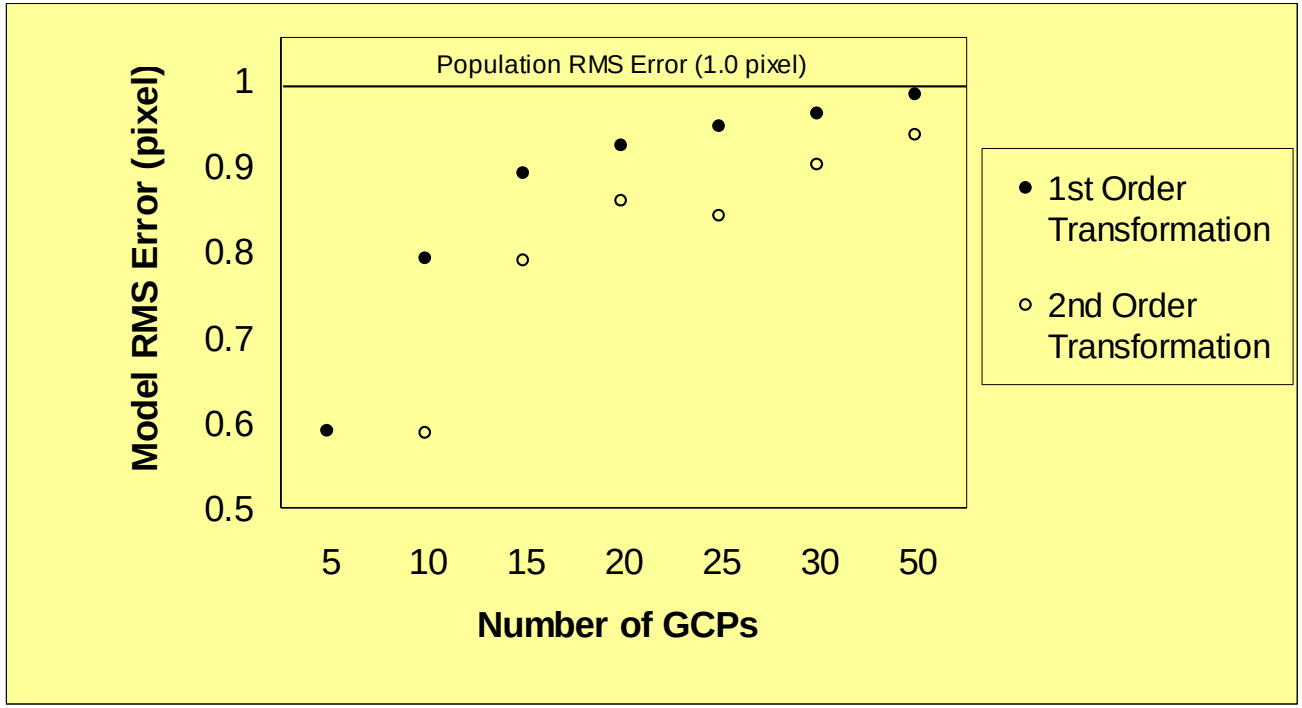
- **Theoretical Issues (GCP's, Grain Size, Classes)**
- **Firescar Database 1950-1997**
- **Comparisons with Landsat Imagery**
- **Detailed Analysis of Land-Cover Change:**

  1983 Rosie Creek Fire

  - **Pre-fire Air Photos and Landsat MSS Imagery**
  - **Immediate Post-fire Air Photos and Landsat TM Imagery**
  - **Decadal Post-fire Air Photos and Landsat TM imagery**

Potential Bias in Land Cover Change Estimates Due to Positional Errors

- Bias can occur at any spatial scale
- False change may exceed real landscape change



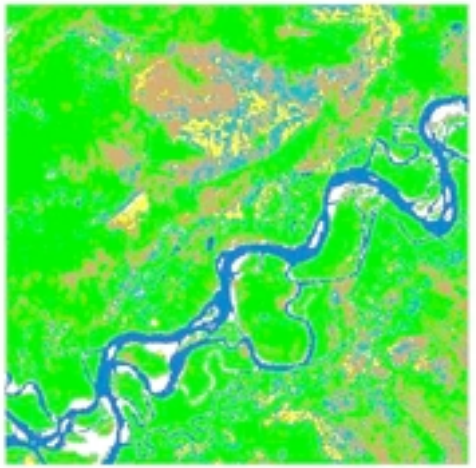
Subpixel rectification error may be optimistic:

- **model error varies with GCP sample size**
- **model error varies with transformation order**

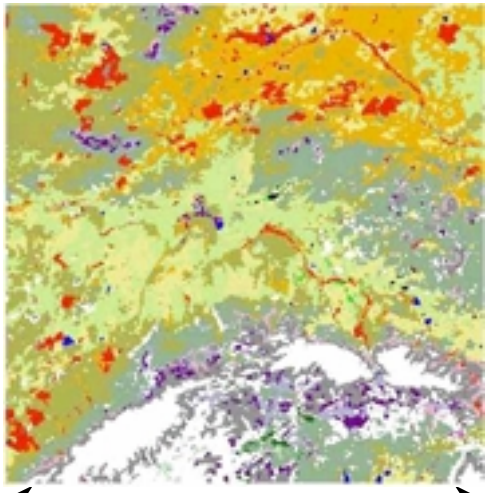
Landsat TM 20 Classes

10 KM

Landsat TM 6 General Classes

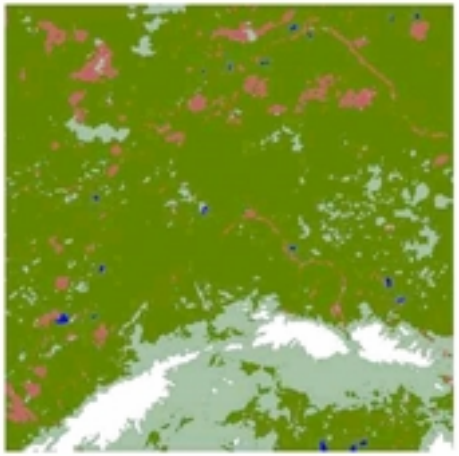


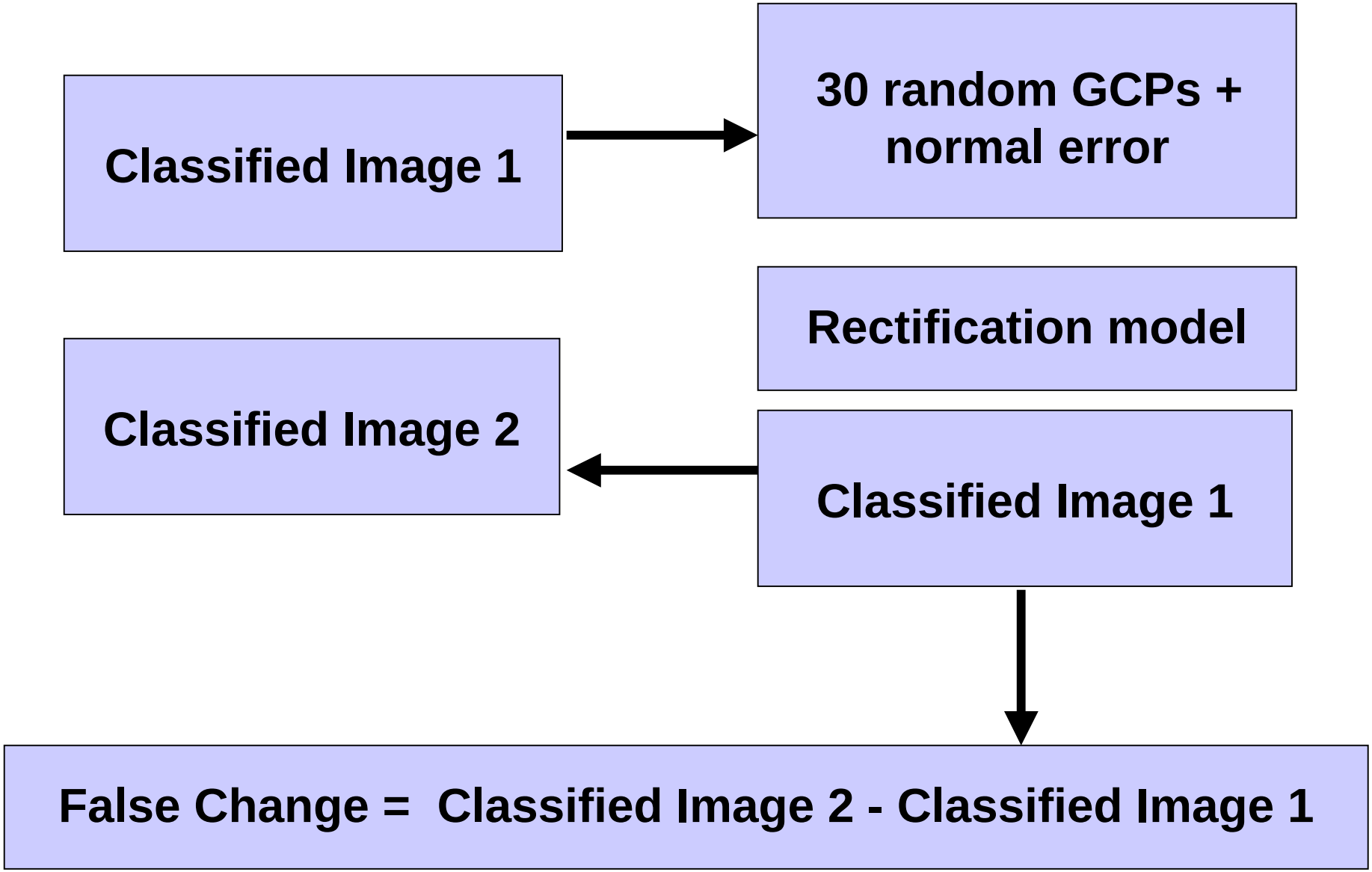
AVHRR 20 Classes



500 KM

AVHRR 5 General Classes




Classified Image 1
30 random GCPs + normal error
Rectification model
Classified Image 2
Classified Image 1
False Change = Classified Image 2 - Classified Image 1

	20 class, 25m pixel		20 class, 1km pixel		6 class, 25m pixel		5 class, 1km pixel	
	Co-registration RMS error	Percent Change	Co-registration RMS error	Percent Change	Co-registration RMS error	Percent Change	Co-registration RMS error	Percent Change
Trial#1	1.10	7.6	0.72	10.9	1.10	8.4	0.86	1.4
Trial#2	0.86	23.7	0.89	14.3	0.73	8.2	0.87	3.5
Trial#3	1.00	8.6	0.89	20.4	0.81	10.1	0.76	2.0
Trial#4	0.75	33.2	0.95	1.8	0.94	8.5	0.96	0.1
Trial#5	0.97	5.9	1.01	13.9	0.89	15.0	0.96	0.5
Trial#6	1.06	9.7	0.94	7.1	1.02	2.2	0.97	2.7
Trial#7	0.93	8.8	0.86	6.6	1.01	10.6	0.96	1.2
Trial#8	0.71	16.1	1.01	5.4	1.09	5.8	0.99	0.6
Trial#9	0.86	4.2	1.00	10.1	1.01	4.4	0.93	1.1
Trial#10	0.90	19.8	0.82	8.4	0.87	14.2	0.96	0.9

- **Landscape metric of heterogeneity not useful; bias in landscape change varied by trial**
- **Bias in landscape change was generally more significant with heterogeneous landscapes**
- **Subpixel co-registration may not solve the problem**

Change Detection in Interior Alaska

- Theoretical Issues (GCP's, Grain Size, Classes)
- **Firescar Database 1950-1997**
- Comparisons with Landsat Imagery
- Detailed Analysis of Land-Cover Change:

  1983 Rosie Creek Fire

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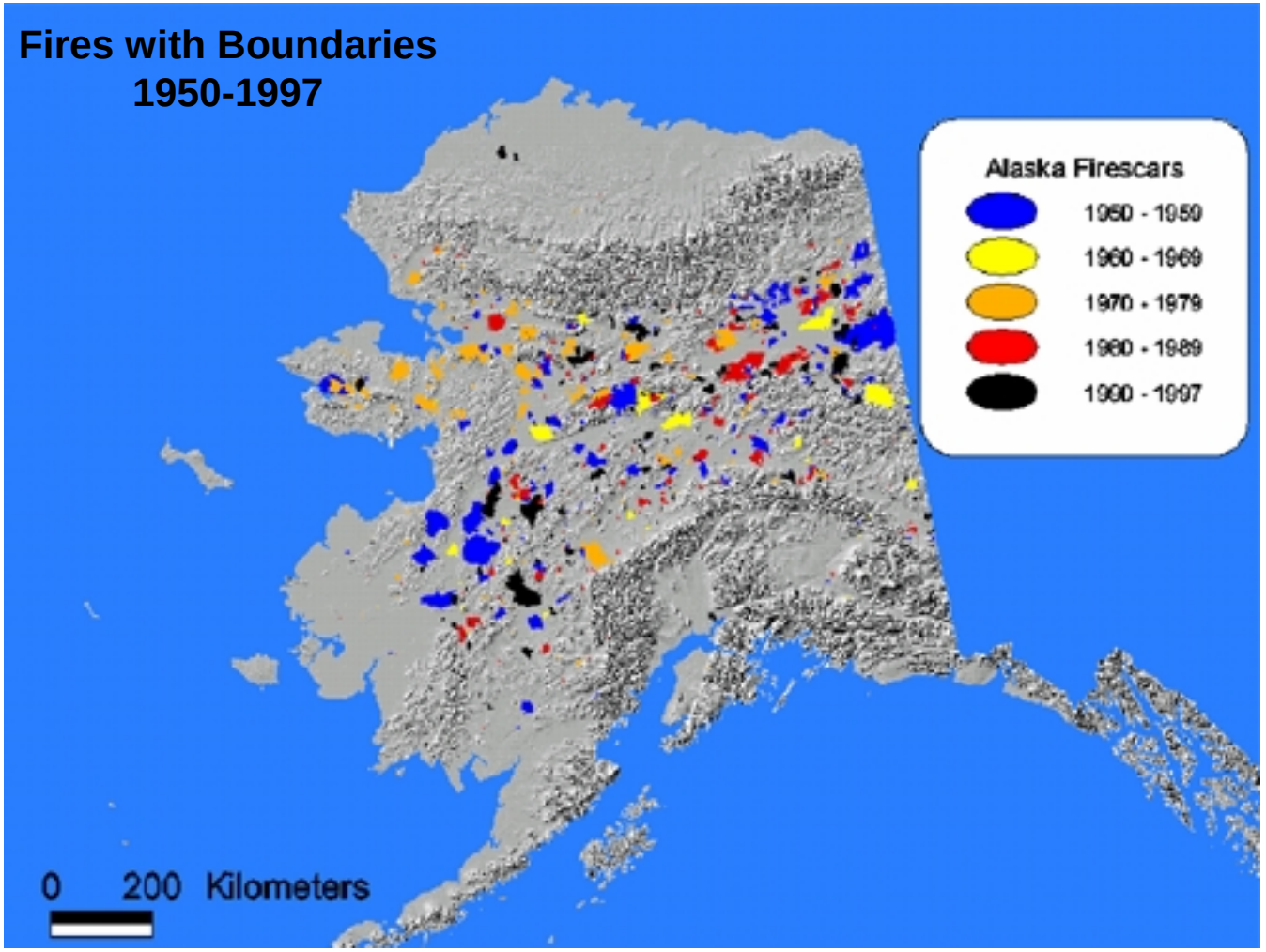
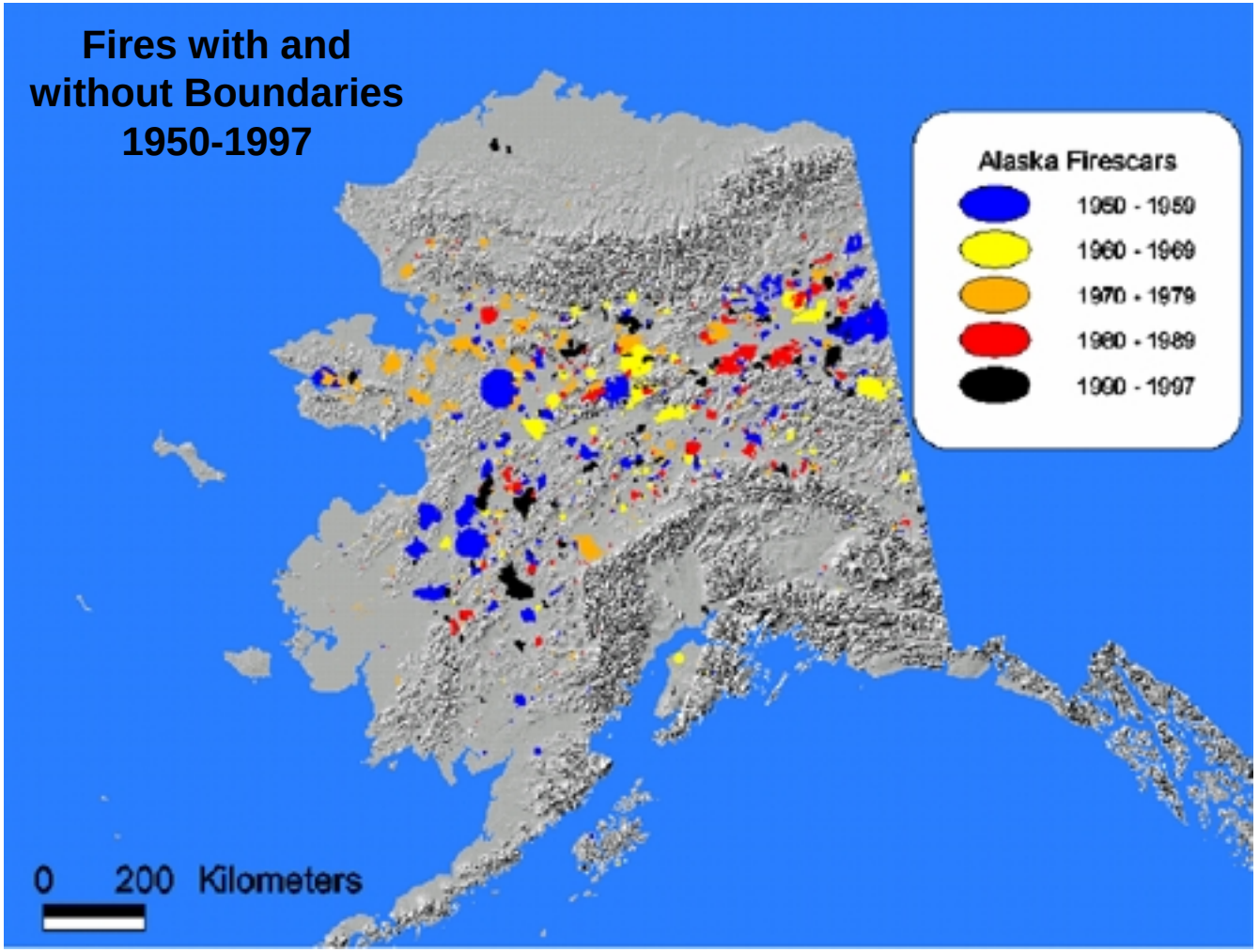
  - Decadal Post-fire Air Photos and Landsat TM imagery


Fires with Boundaries
1950-1997
Alaska Firescars
1950 - 1959
1960 - 1969
1970 - 1979
1980 - 1989
1990 - 1997
0 200 Kilometers


Fires with and without Boundaries 1950-1997
Alaska Firescars
1950 - 1959
1960 - 1969
1970 - 1979
1980 - 1989
1990 - 1997
0 200 Kilometers

Change Detection in Interior Alaska

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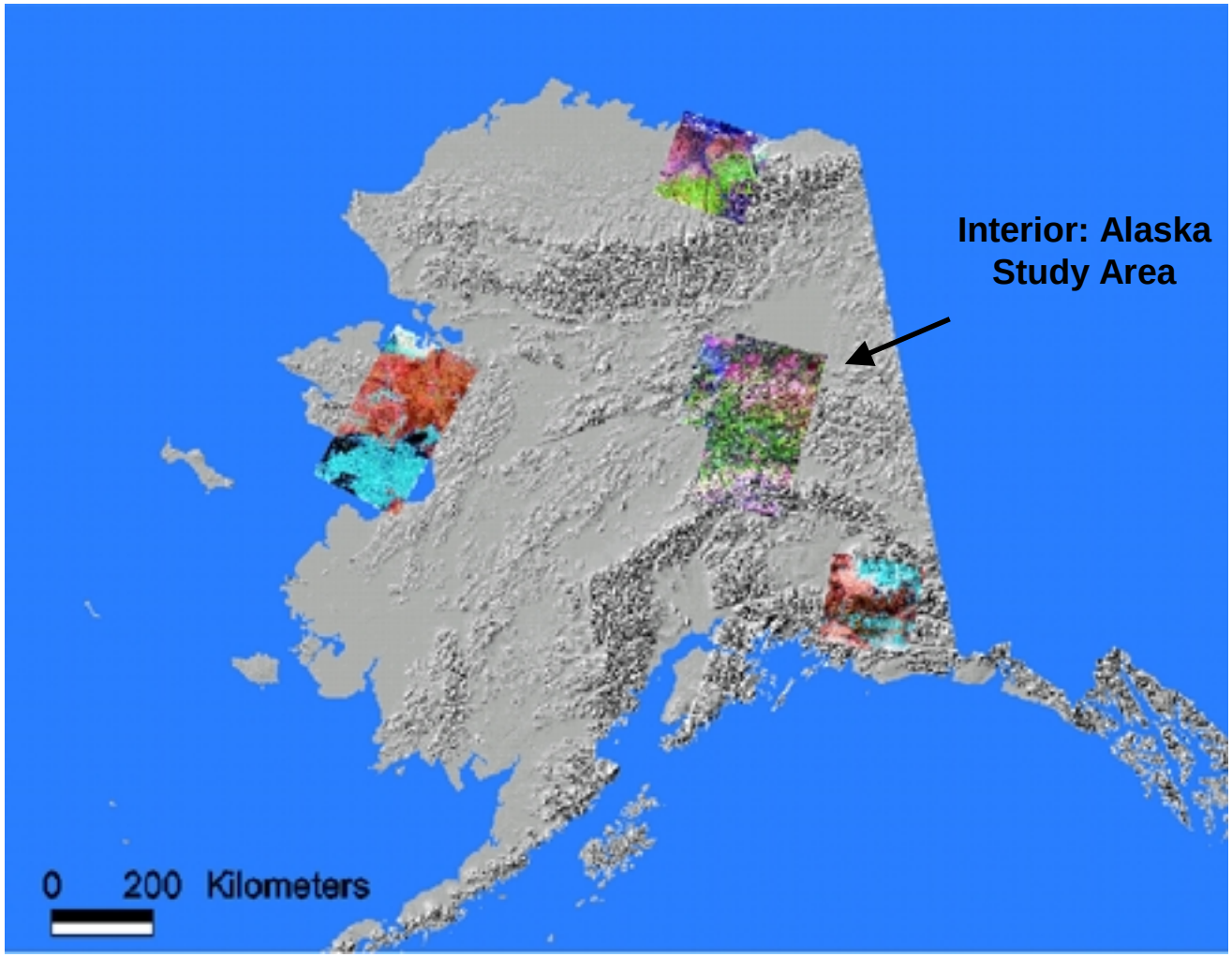
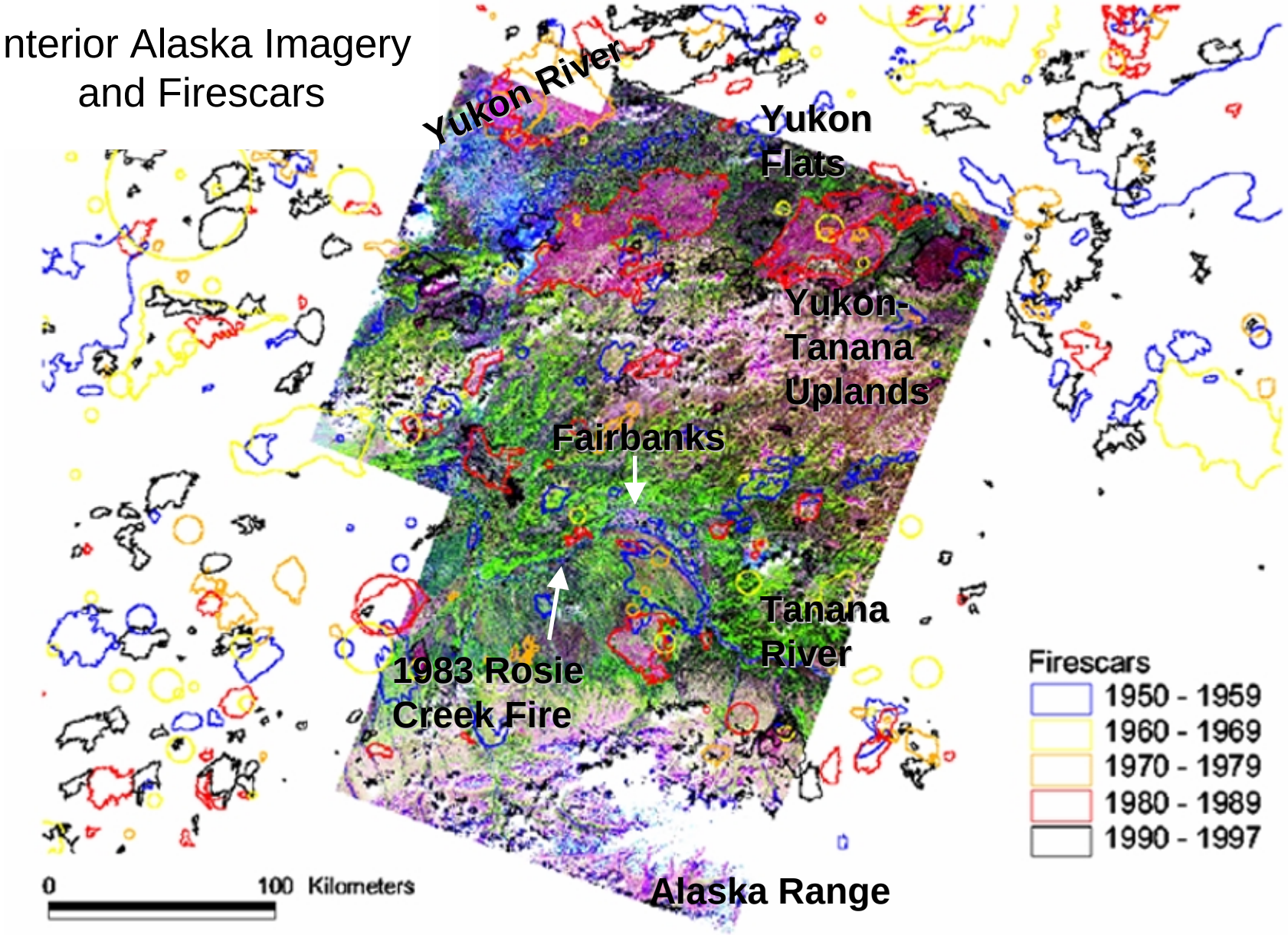

Interior: Alaska
Study Area
0 200 Kilometers

Interior Alaska Imagery and Firescars



Change Detection in Interior Alaska

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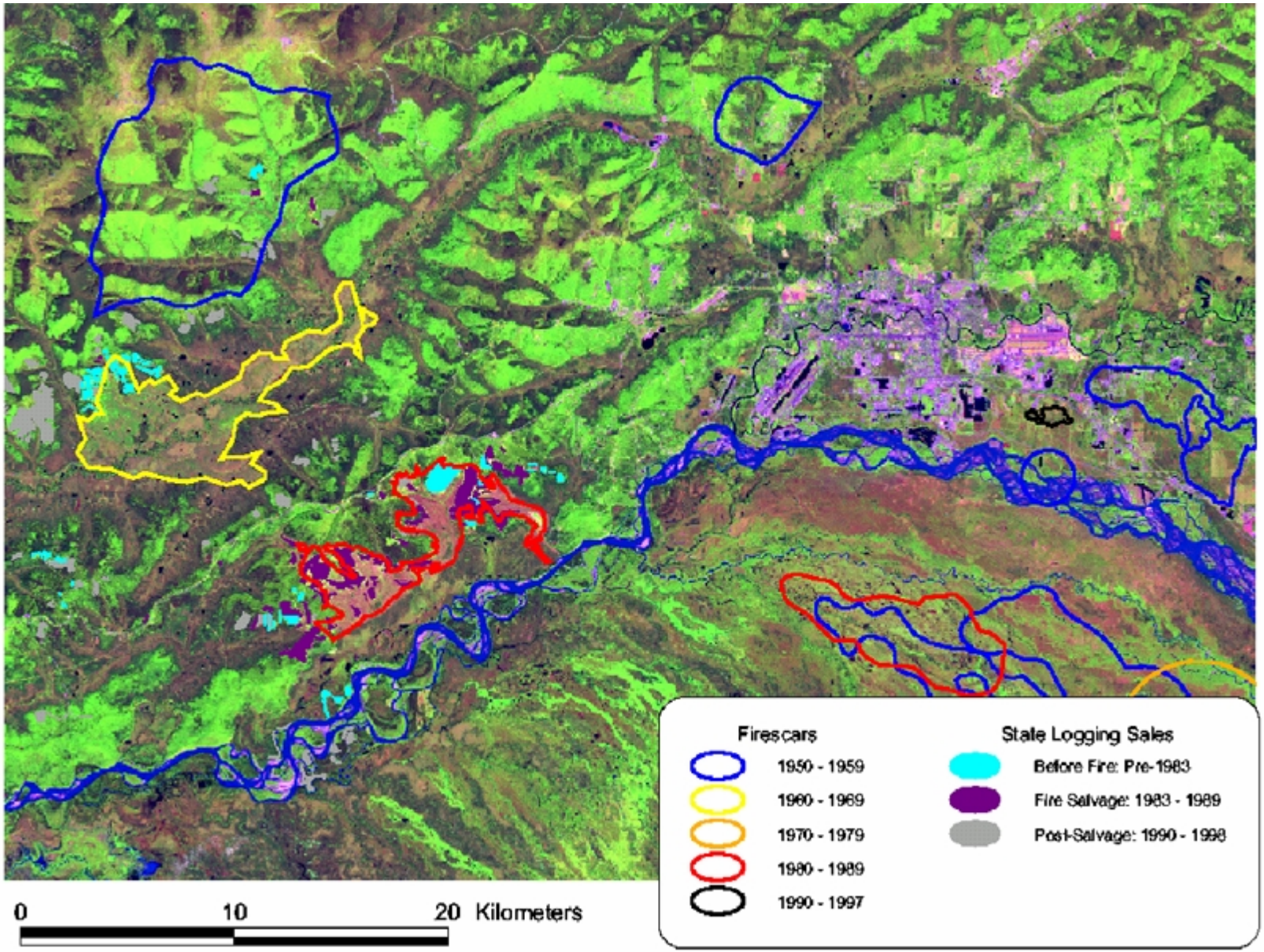
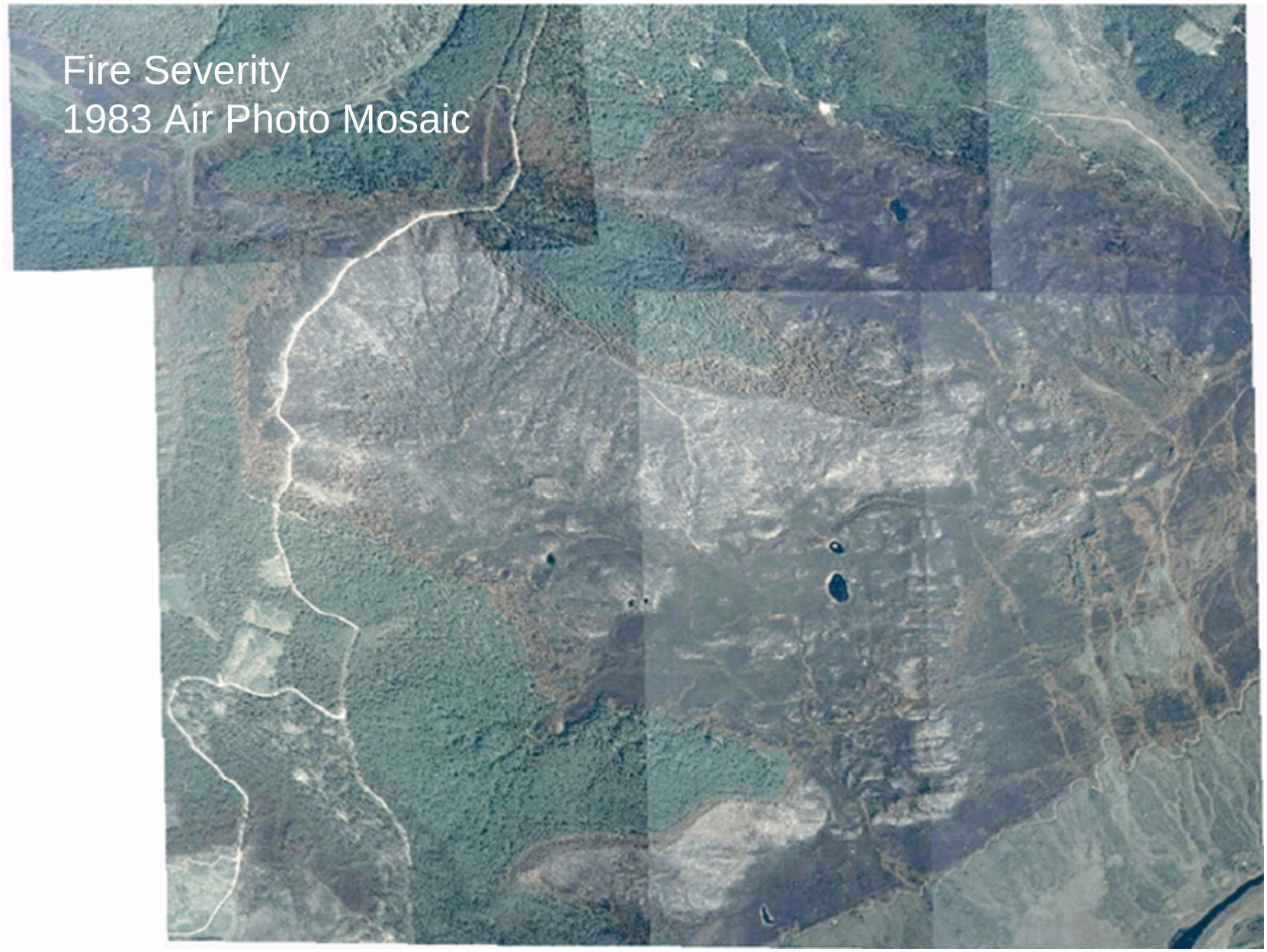
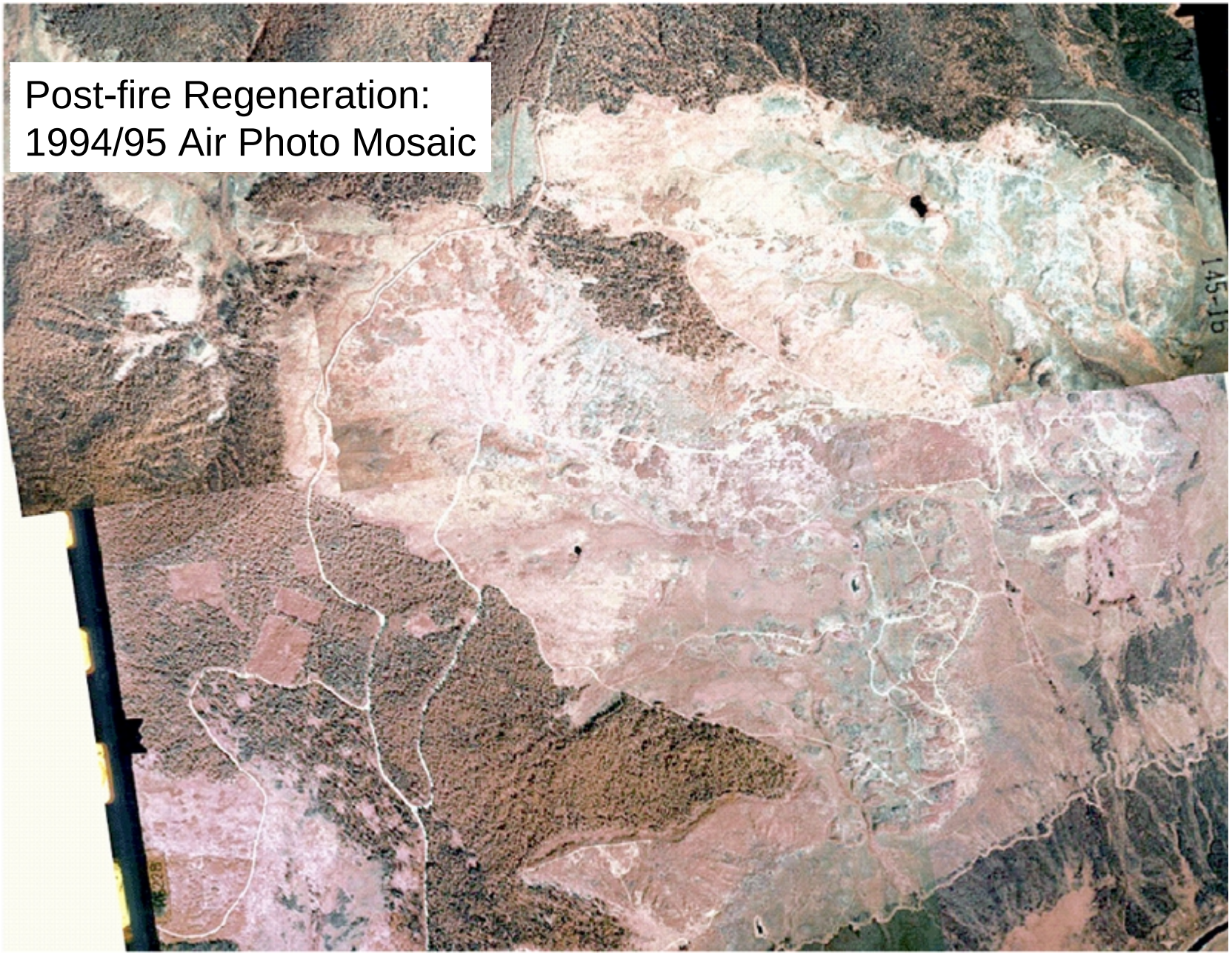
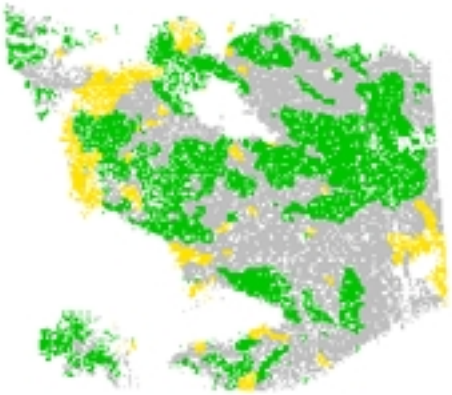

Firescars
1950 - 1959
1960 - 1969
1970 - 1979
1980 - 1989
1990 - 1997
State Logging Sales
Before Fire: Pre-1983
Fire Salvage: 1983 - 1989
Post-Salvage: 1990 - 1998
0
10
20 Kilometers

Pre-Fire Vegetation
1971 Air Photo Mosaic


Fire Severity
1983 Air Photo Mosaic

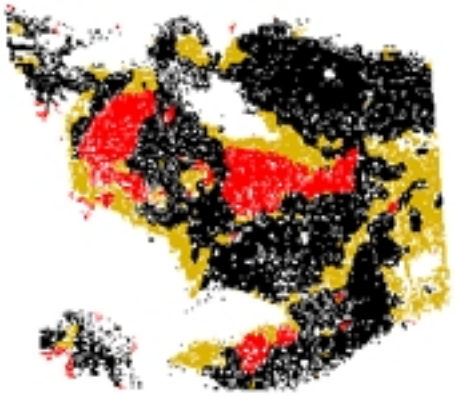

Post-fire Regeneration:
1994/95 Air Photo Mosaic

Predicting Post-fire Regeneration in the 1983 Rosie Creek Fire



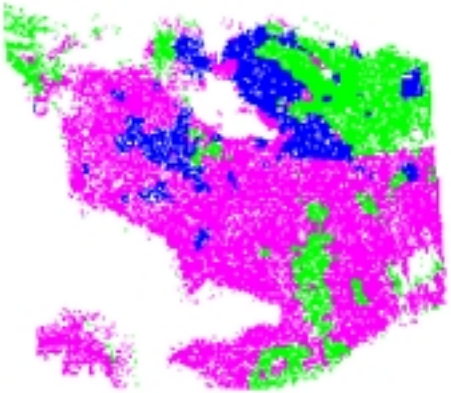
1971 Pre-fire Vegetation

- 0=Low Muskeg
- 1=Spruce Forest
- 2=Hardwood Forest



1983 Fire Severity

- 0=Unburned / Nonvegated
- 1=Light Severity
- 2=Moderate Severity
- 3=High Severity



1994/95 Dominant Post-Fire Vegetation

- 0=Unburned / Nonvegetated
- 1=Grass and Bare Ground
- 2=Spruce / Labrador Tea
- 3=Shrubs

Vegetation Regeneration after the 1983 Rosie Creek Fire (Bonanza Creek LTER)

Developing a Predictive Model of Post-fire Regeneration Classes

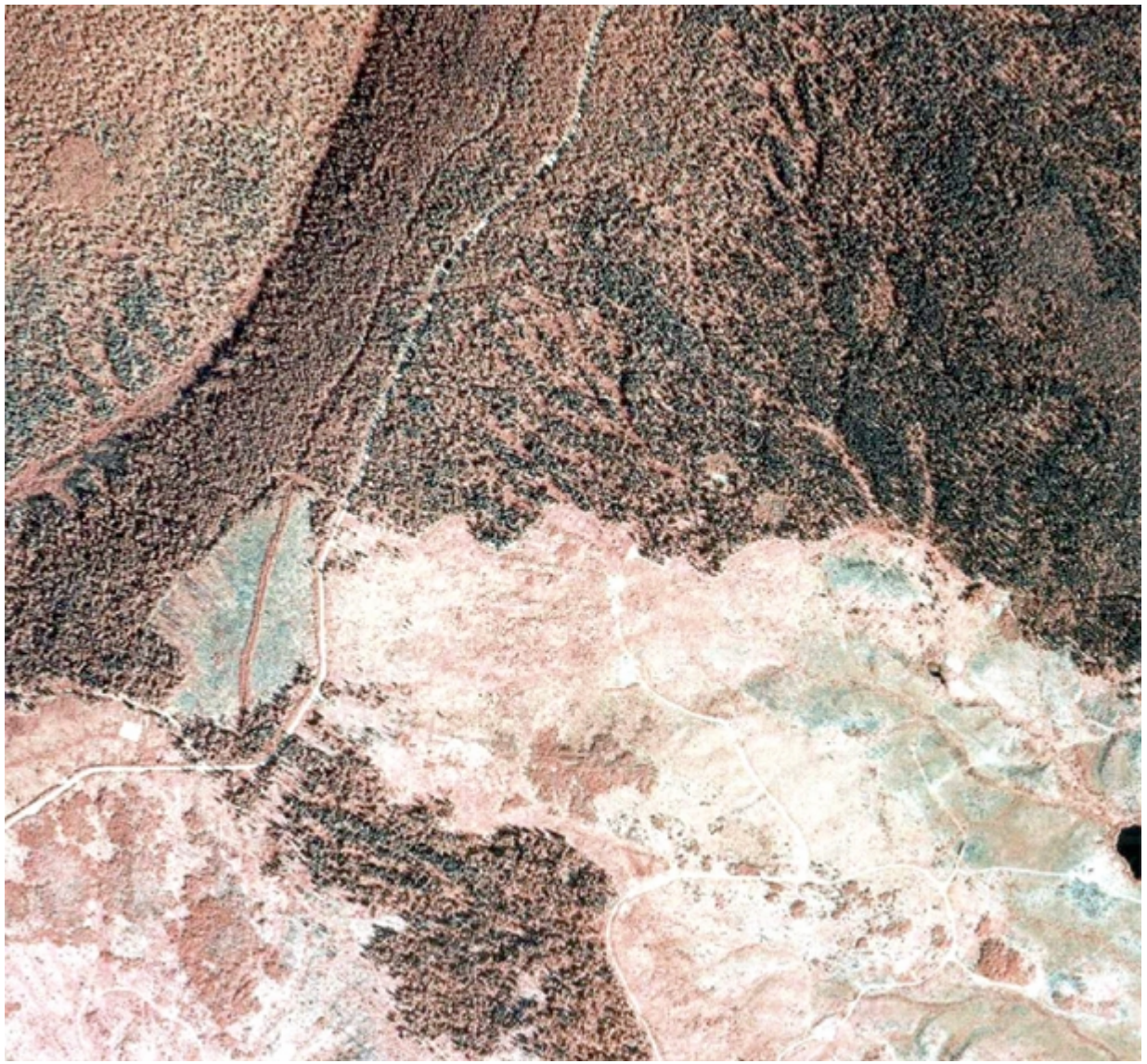
• Remote sensing as primary data source: aerial photography and satellite imagery obtained before and after the fire.

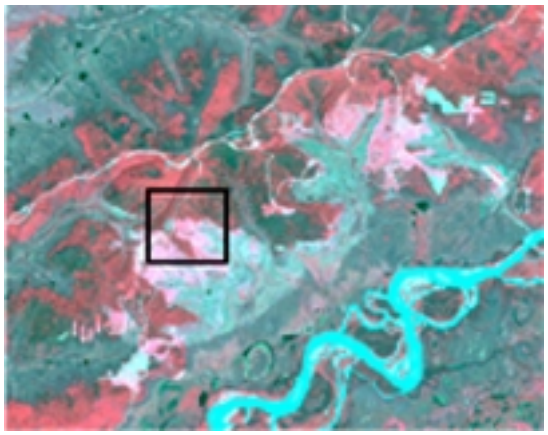
•On most burned forest sites in Interior Alaska, shrub regeneration dominates a decade after the fire. What conditions are most likely to lead to alternative successional trajectories?

Air Photo Class	Pixel Count	Shrub Regen. Proportion
Pre-fire Hardwood	967	0.903
Pre-fire Muskeg	5304	0.609
Pre-fire Spruce	4466	0.549
Light Burn	2262	0.743
Moderate Burn	6976	0.508
Severe Burn	1499	0.888

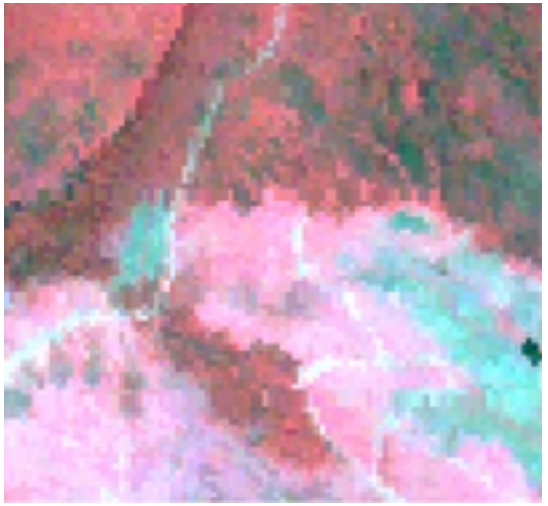
•Topographic position, salvage logging status, and field measurements of biomass, soil, and permafrost will be used as additional explanatory variables.

Bonanza Creek Experimental Forest (1983 Rosie Creek Fire)
Decadal Post-Fire: 1994 Air Photo and 1991 Landsat TM Imagery





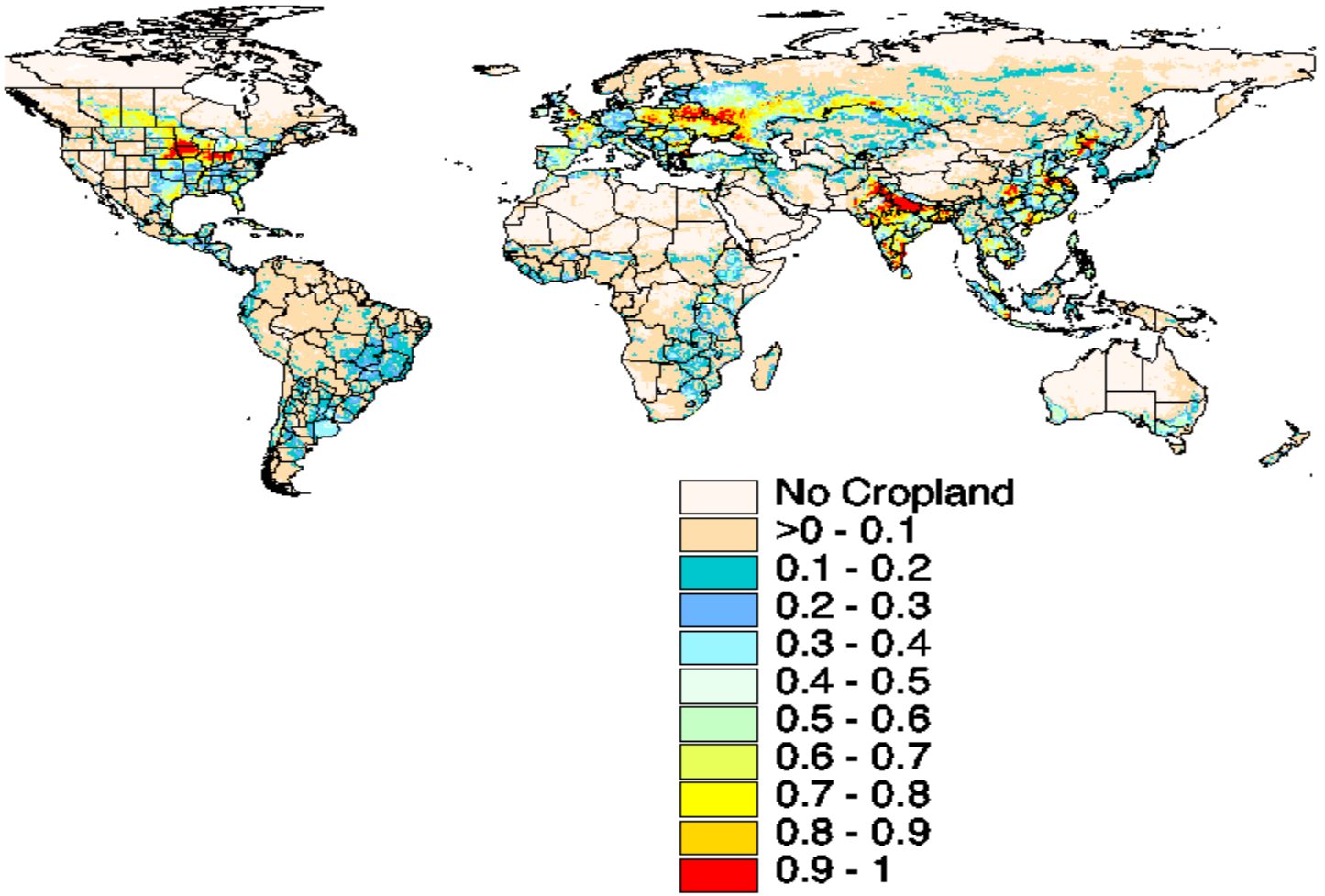
= 2x2 km



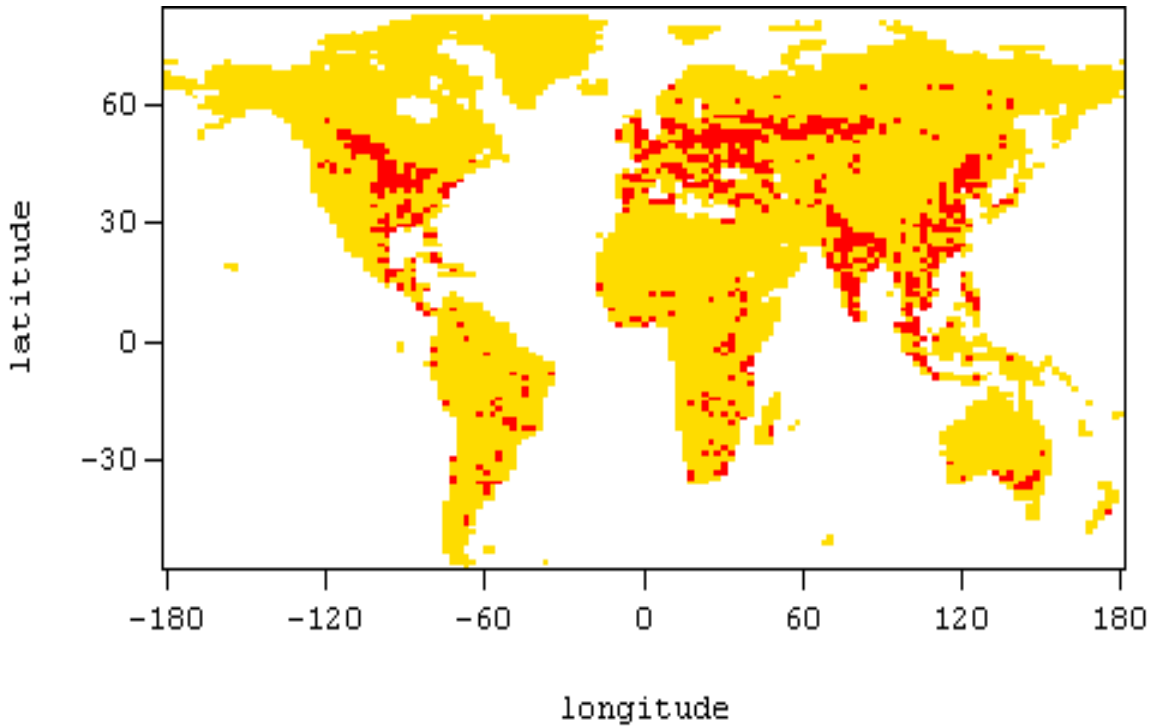
Global Historical Agricultural Land-Use: Development of a 0.5º Boolean Data Set

- Based on 1-km data set developed by Ramankutty and Foley (1998)
  - Based on version 1.2 DISCover data set
  - Based on 1992 crop cover inventory
  - Backcast to 1860 based on historical inventory
  - Aggregated to 0.5º as fractional crop cover
- Mixture at 5º to minimize bias
- Time-filtered (9-years) to minimize blinking

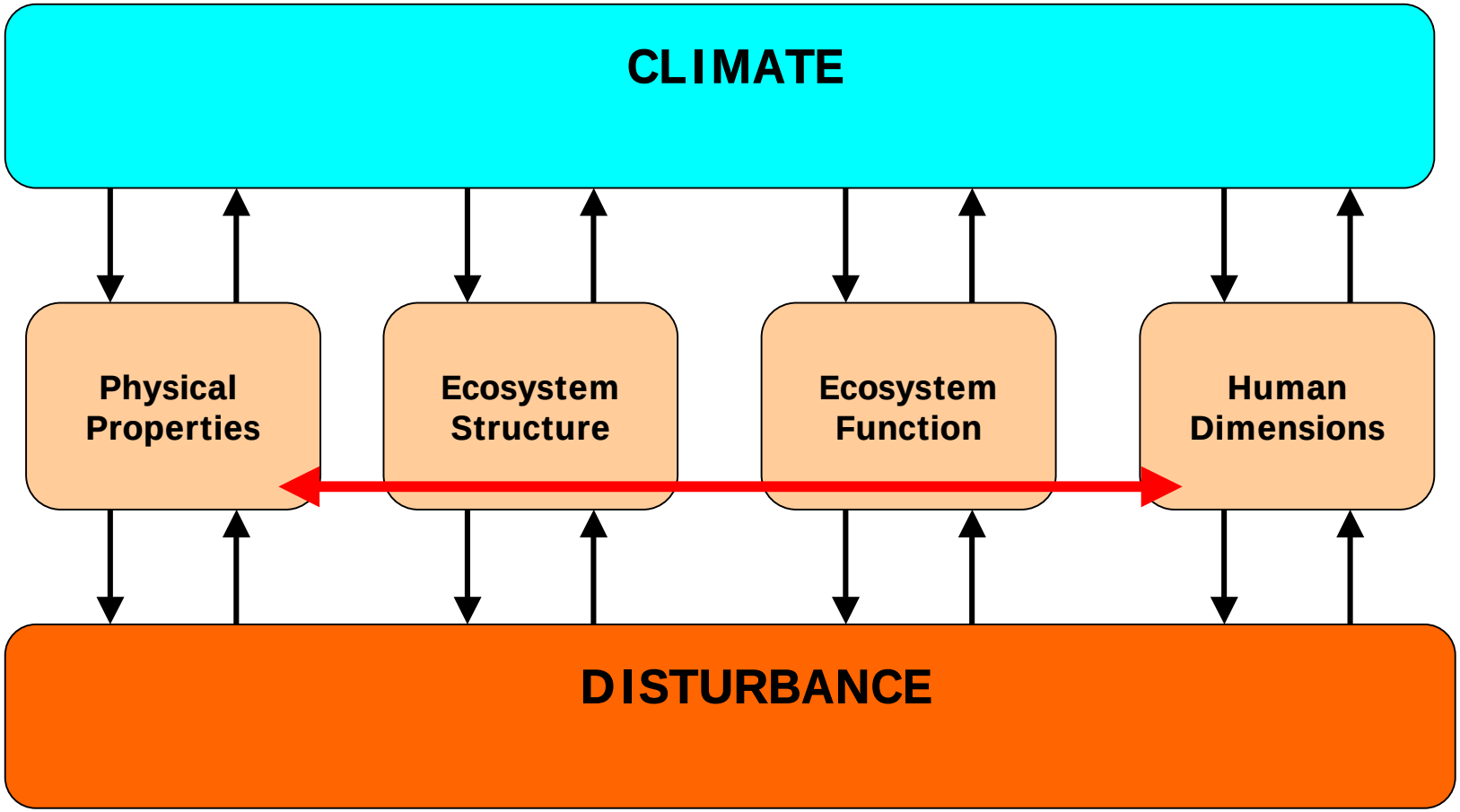
Global Crop Cover in 1992 (0.5 deg resolution)
(Ramankutty and Foley, 1998)



Global Crop Cover in 1992 (0.5 Degree Boolean Data Set)



Modeling Framework for Investigating Global Change in High Latitude Ecosystems



Components of the Modeling Framework

- **Physical Properties of Terrestrial Ecosystems:**
  Based on Goodrich model of permafrost dynamics
- **Physical Processes and Ecosystem Function:**
  Based on Terrestrial Ecosystem Model (TEM) - version 4.
- **Effects of Disturbance on Ecosystem Function:**
  Based on Terrestrial Ecosystem Model (TEM) - version 4.
- **Modeling the Disturbance Regime:**
  Based on physical and biological properties of ecosystems.
- **Ecosystem Structure and the Disturbance Regime:**
  Based on ALaska FRame-based EcoSystem Code (ALFRESCO)
  Starfield and Chapin. 1996. Ecol. Appl. 6:842-864
- **Modeling Vegetation Dynamics:**
  Development of Dynamic Arctic Vegetation Model (DAVM)
- **Human Dimensions:**
  Based on conceptual model of Chapin, Starfield, and Naylor

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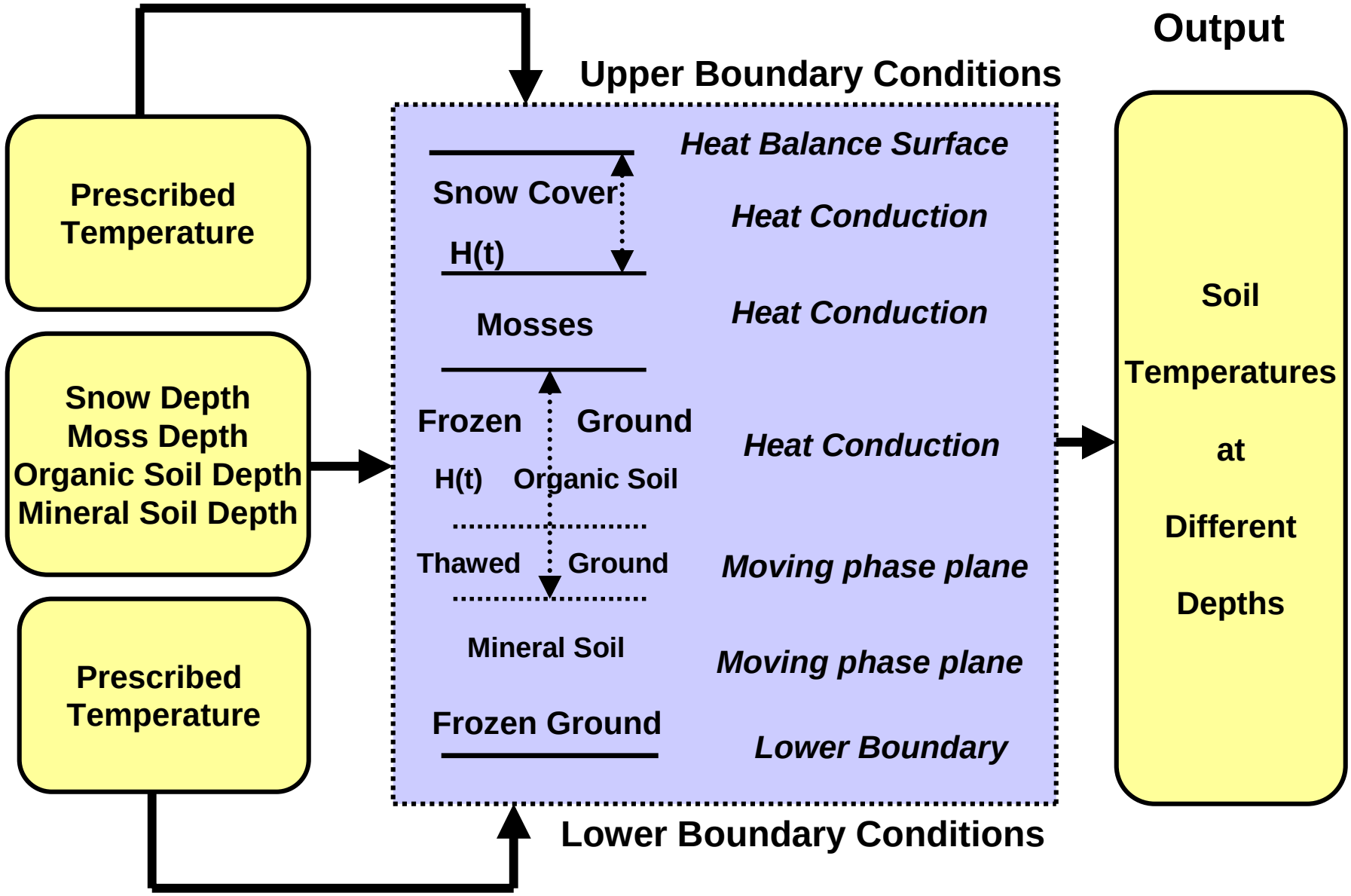
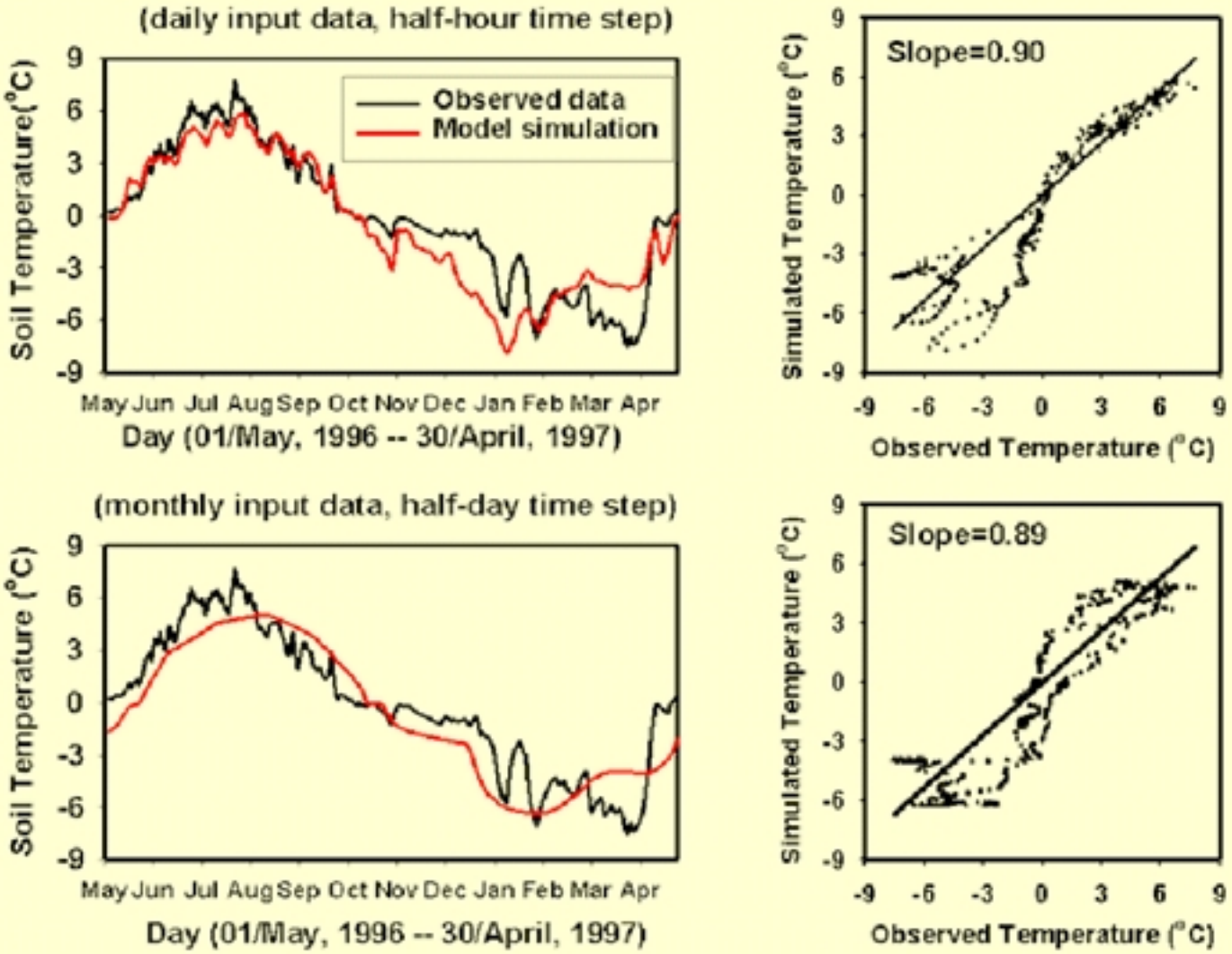
Why is Modeling Permafrost Dynamics Important?

- The dynamics of permafrost influences the physical environment, ecosystem function, ecosystem structure, and the disturbance regime
- The effects of disturbance on permafrost dynamics influences vegetation trajectories after disturbance
- Permafrost is warming in many high latitude regions
- Areas of discontinuous permafrost are most vulnerable to melting and are also regions of higher population density
- Thawing of permafrost has important impacts on humans in high latitude regions



Soil Temperature Model

Soil Temperature Comparison at 23 cm - Daily Output



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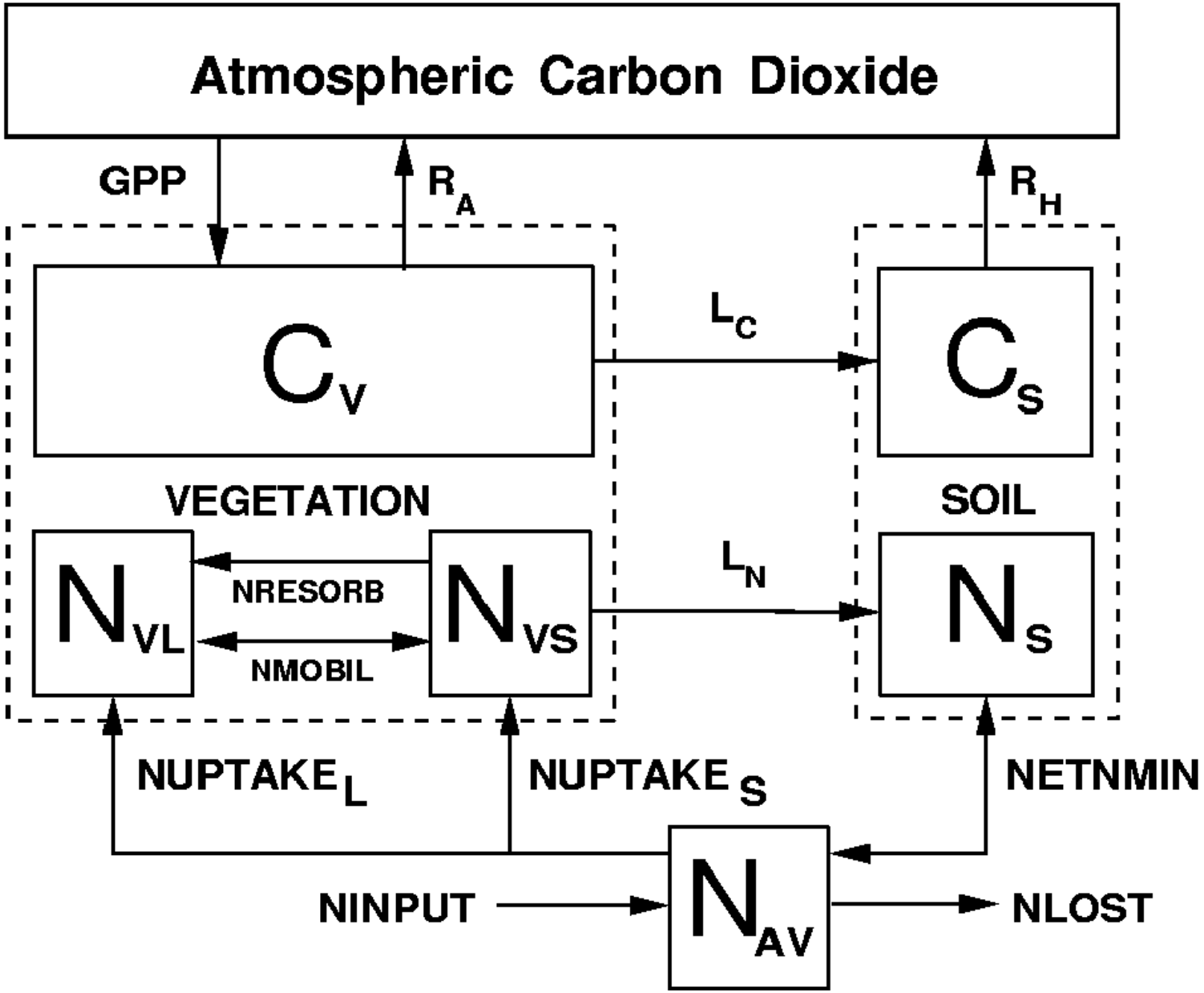
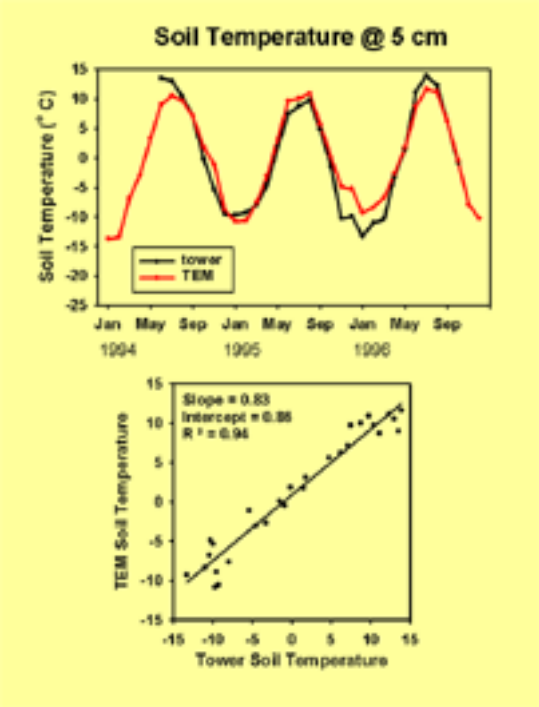
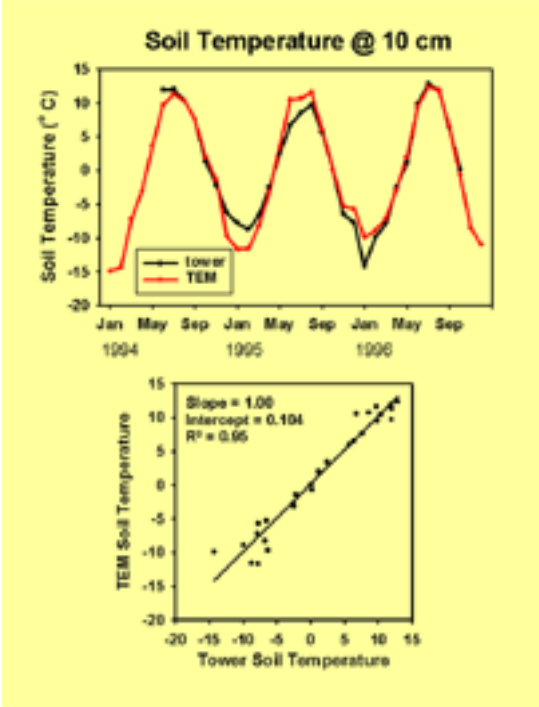
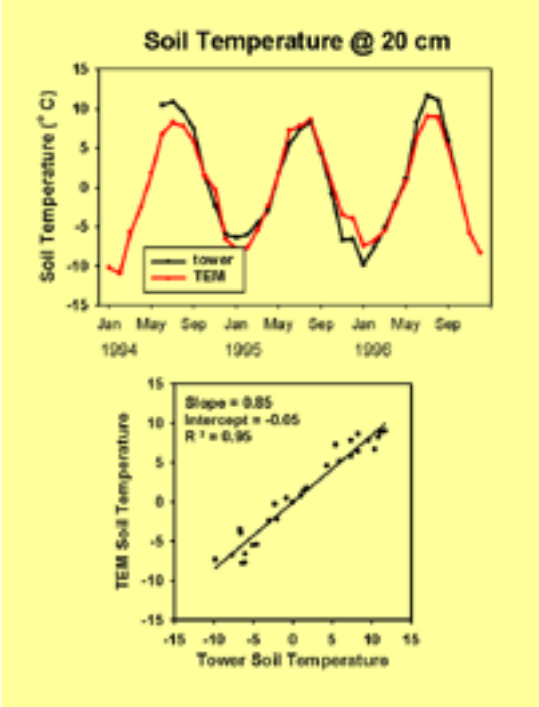

Atmospheric Carbon Dioxide
GPP
R_A
R_H
C_V
L_C
C_S
VEGETATION
SOIL
N_{VL}
NRESORB
NMOBIL
N_{VS}
L_N
N_S
$NUPTAKE_L$
$NUPTAKE_S$
NETNMIN
NINPUT
N_{AV}
NLOST

Simulated and Observed Soil Temperature at the Northern Study Area Old Black Spruce Site (BOREAS)

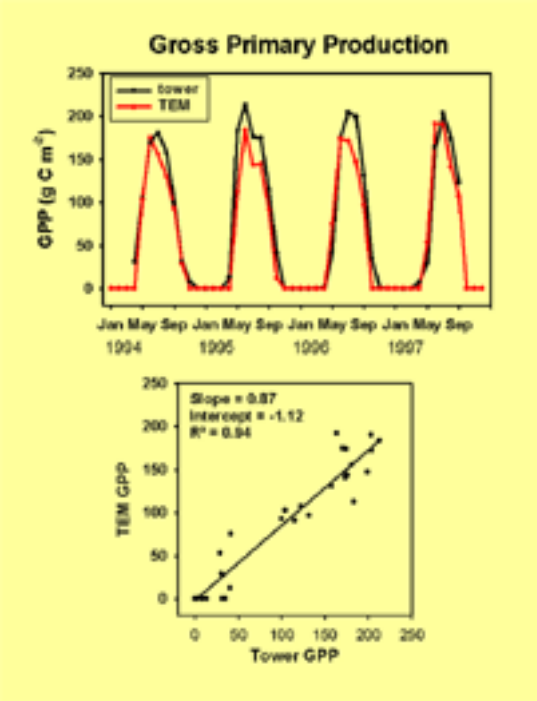


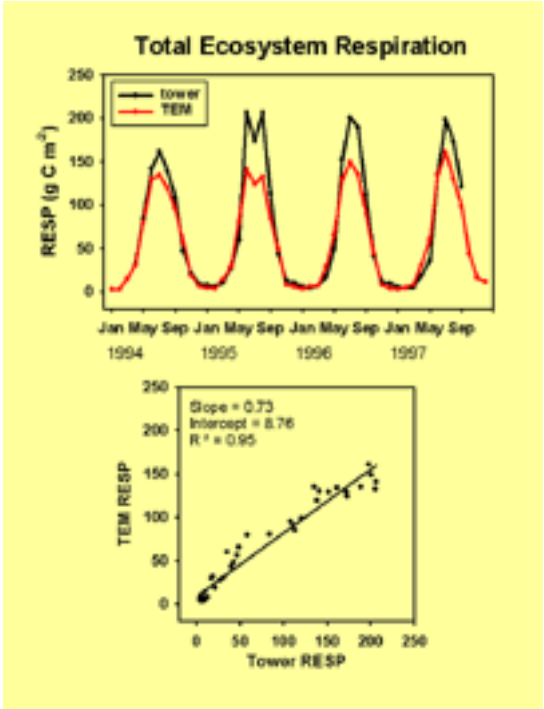


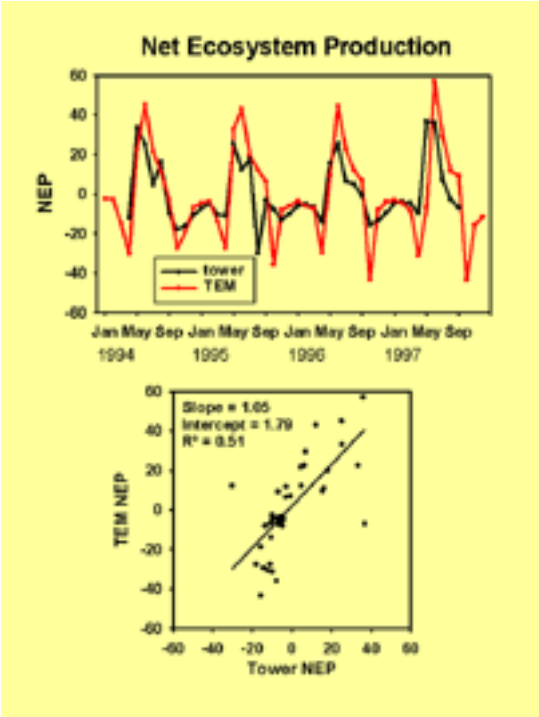


Regressions represent comparisons between simulated and observed soil temperature from June 1994 to Oct. 1996.

Simulated and Field-based Carbon Fluxes at the Northern Study Area Old Black Spruce Site (BOREAS)



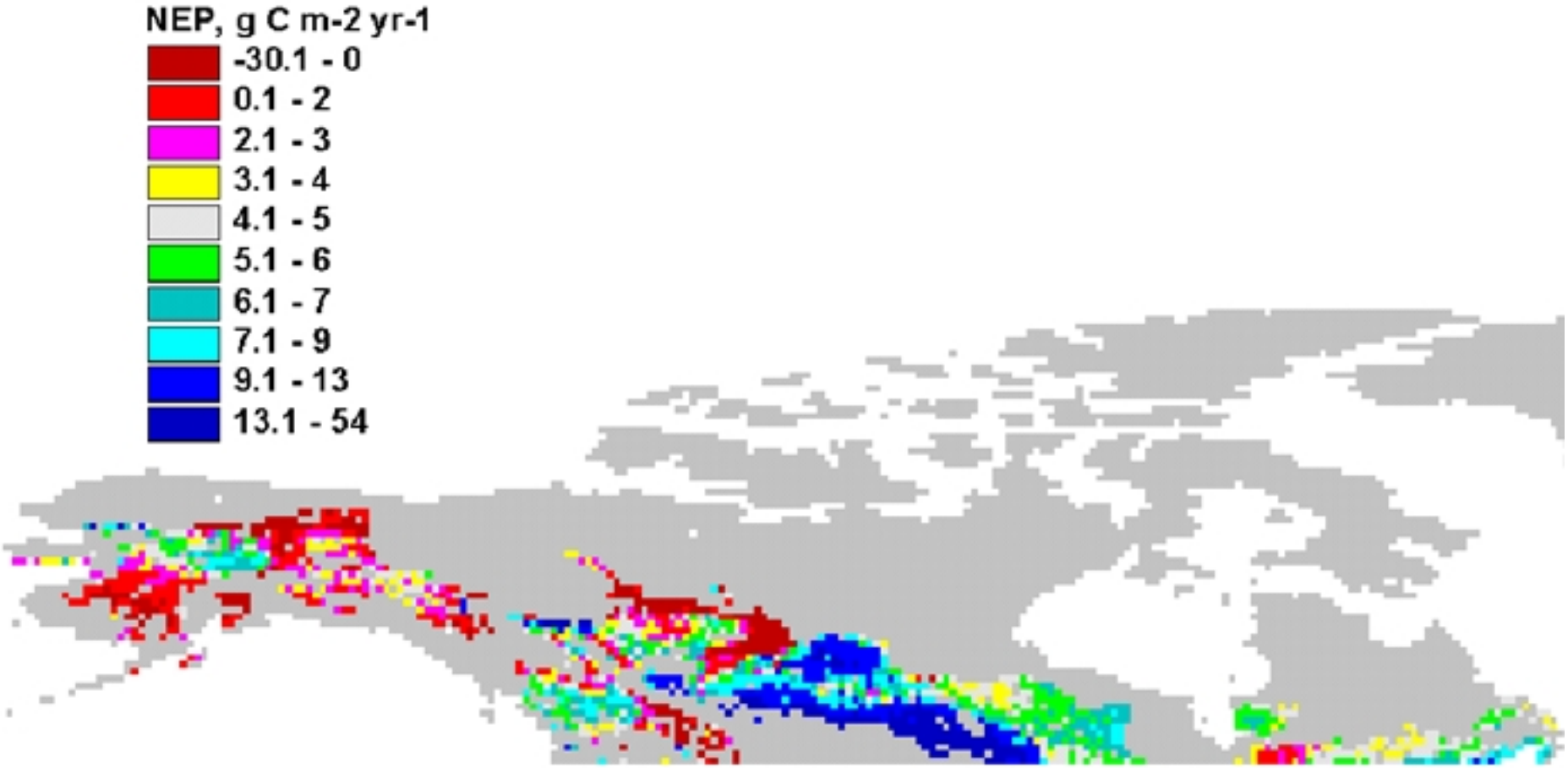




Regressions represent comparisons between simulated and field-based carbon fluxes from April 1994 to Sept 1997.

Changes in Black Spruce Carbon Storage Between 1980 and 1989 in Boreal North America

Climate based on Jones temperature anomalies,
Hulme precipitation anomolies, and Cramer-Leeman's climatology



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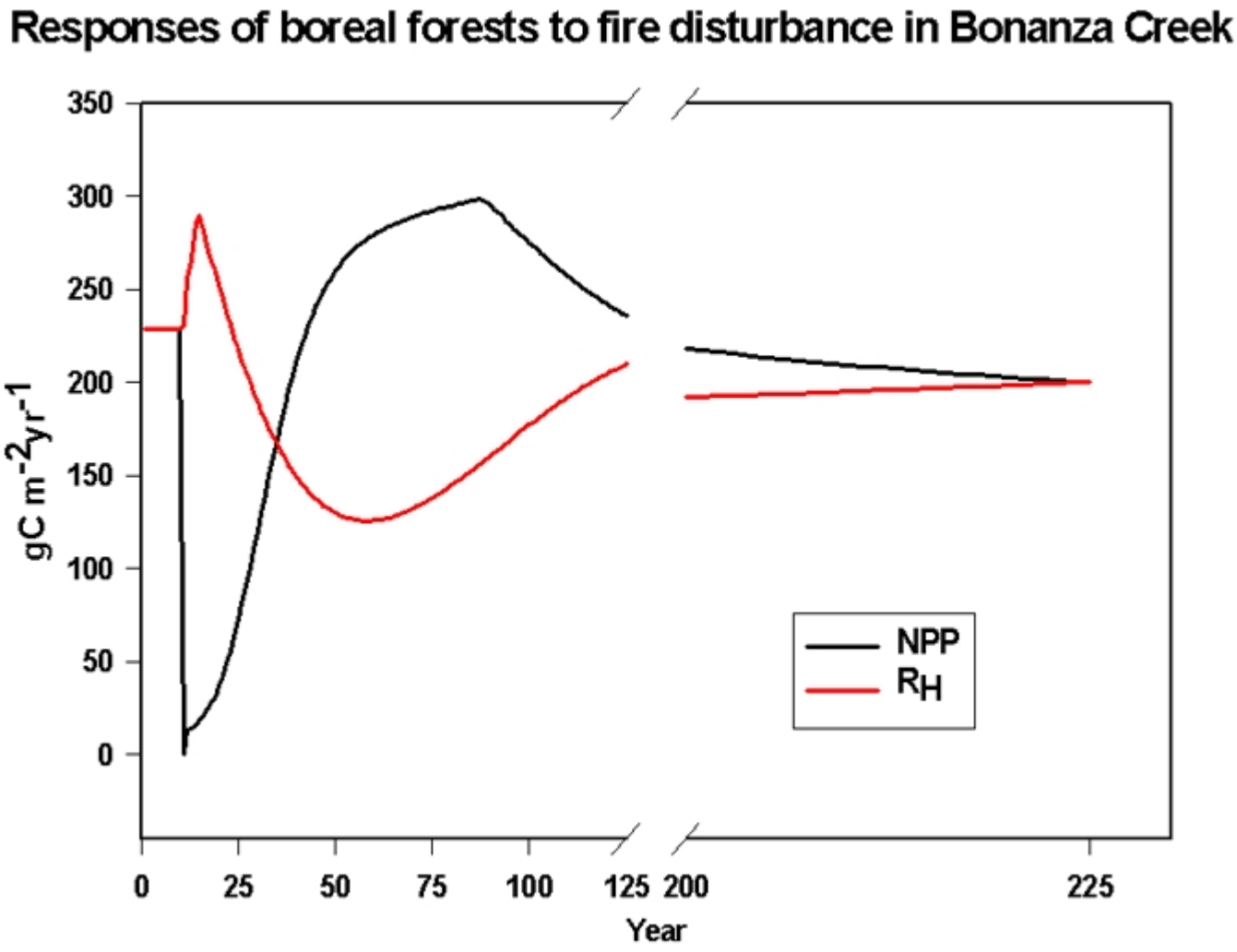
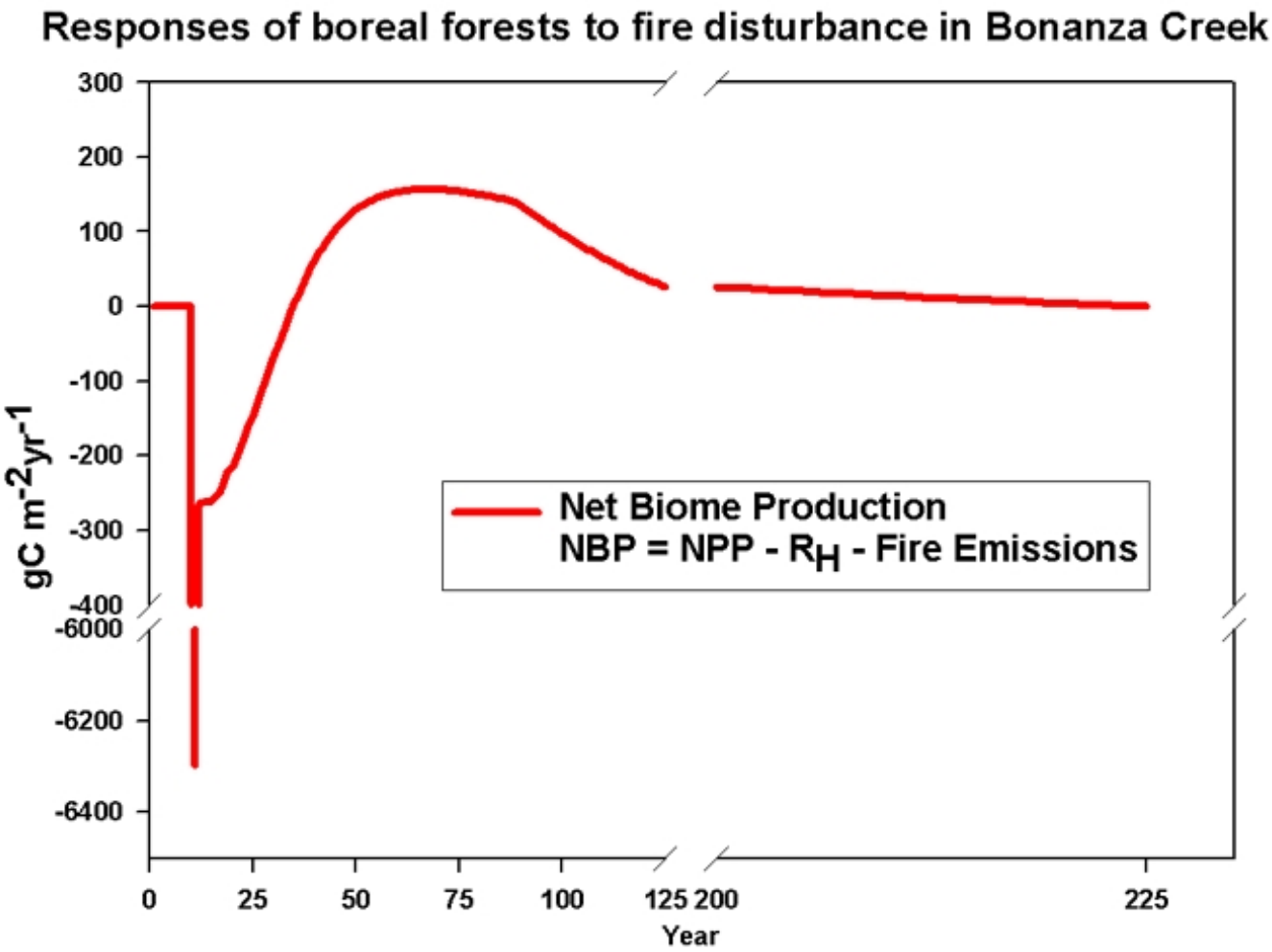
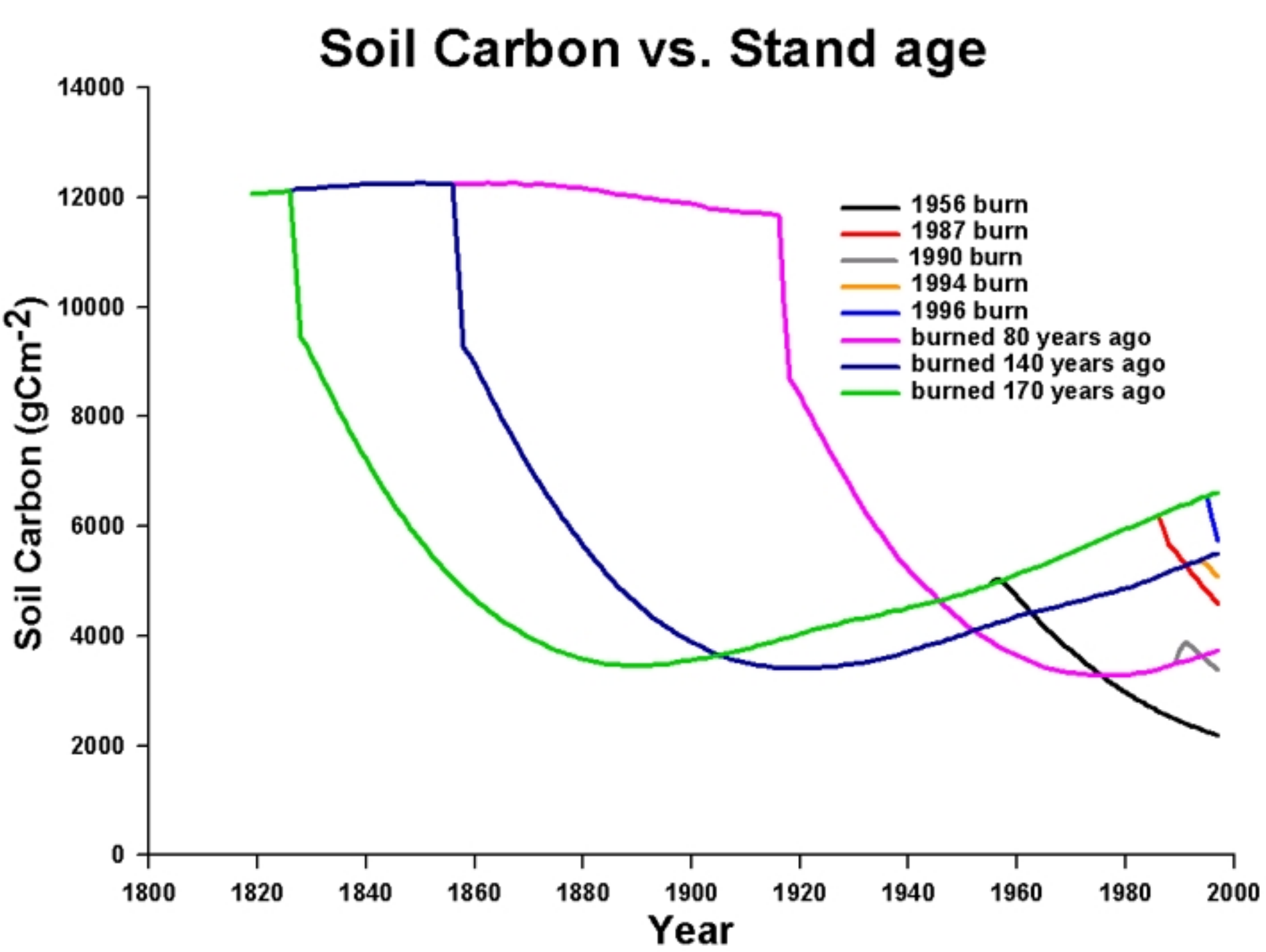
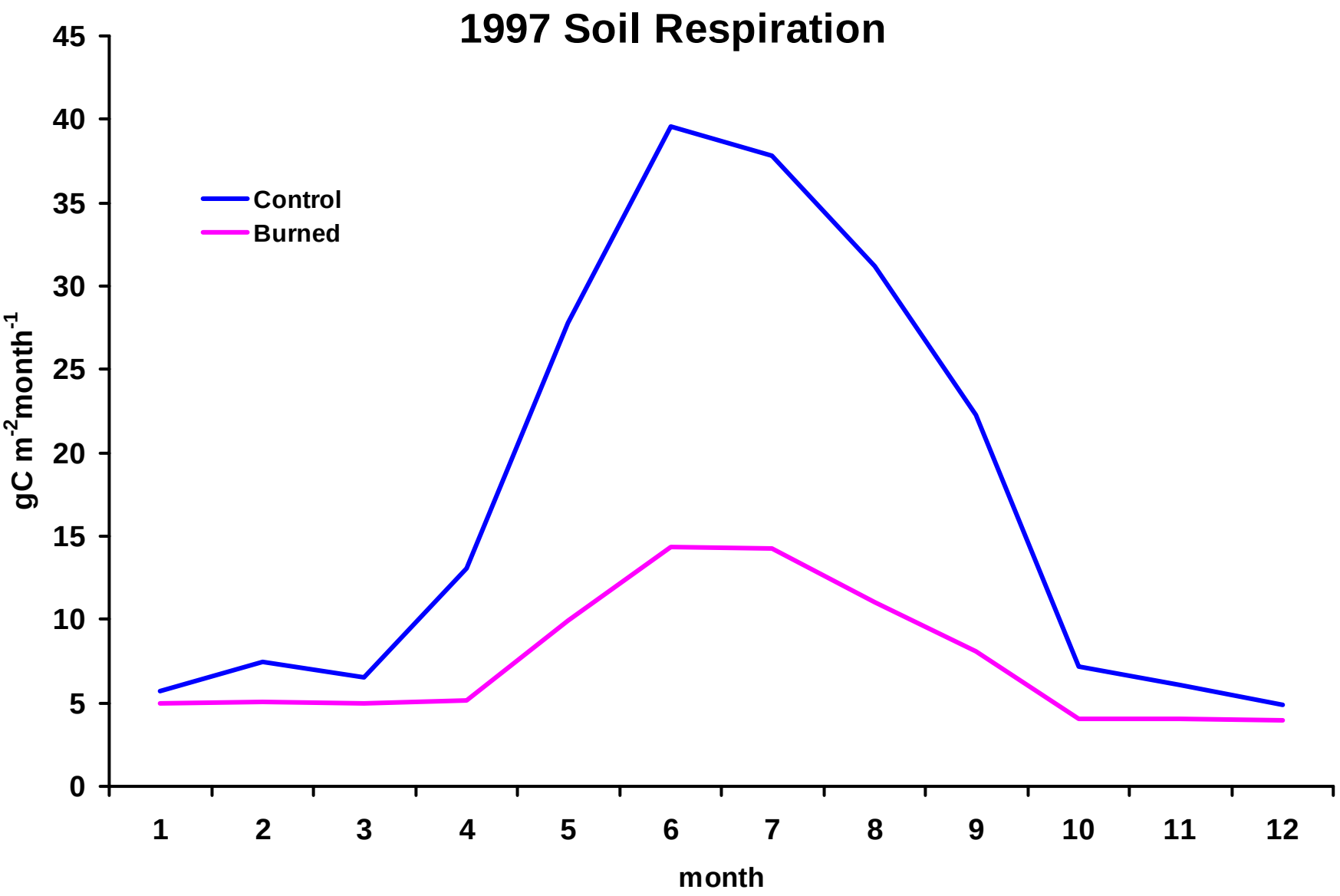
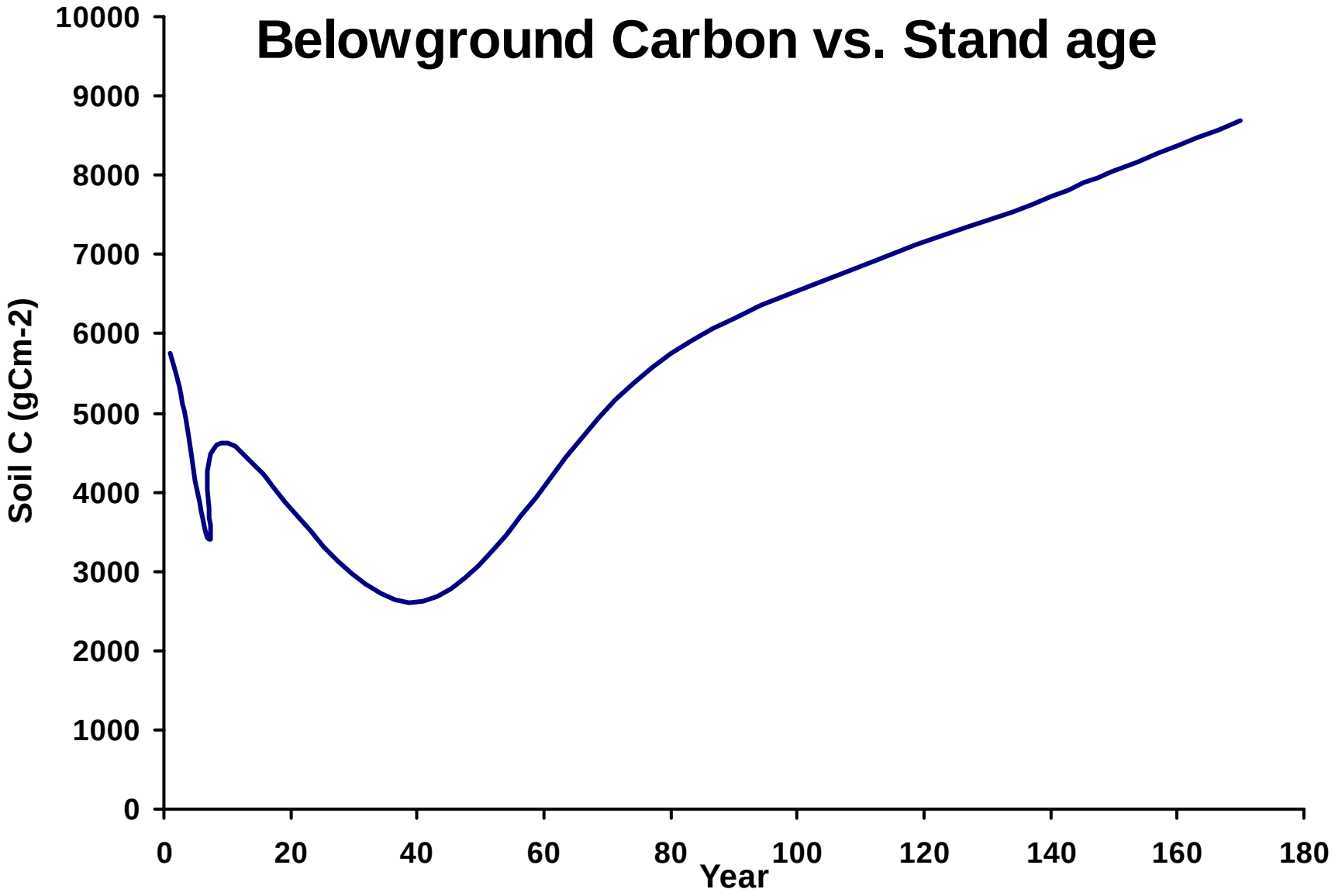

Responses of boreal forests to fire disturbance in Bonanza Creek
350
300
250
200
150
100
50
0
gC m-2yr-1
0
25
50
75
100
125
200
225
Year
NPP
RH


Responses of boreal forests to fire disturbance in Bonanza Creek
300
200
100
0
-100
-200
-300
-400
-6000
-6200
-6400
gC m-2yr-1
Net Biome Production
NBP = NPP - RH - Fire Emissions
0
25
50
75
100
125
200
225
Year

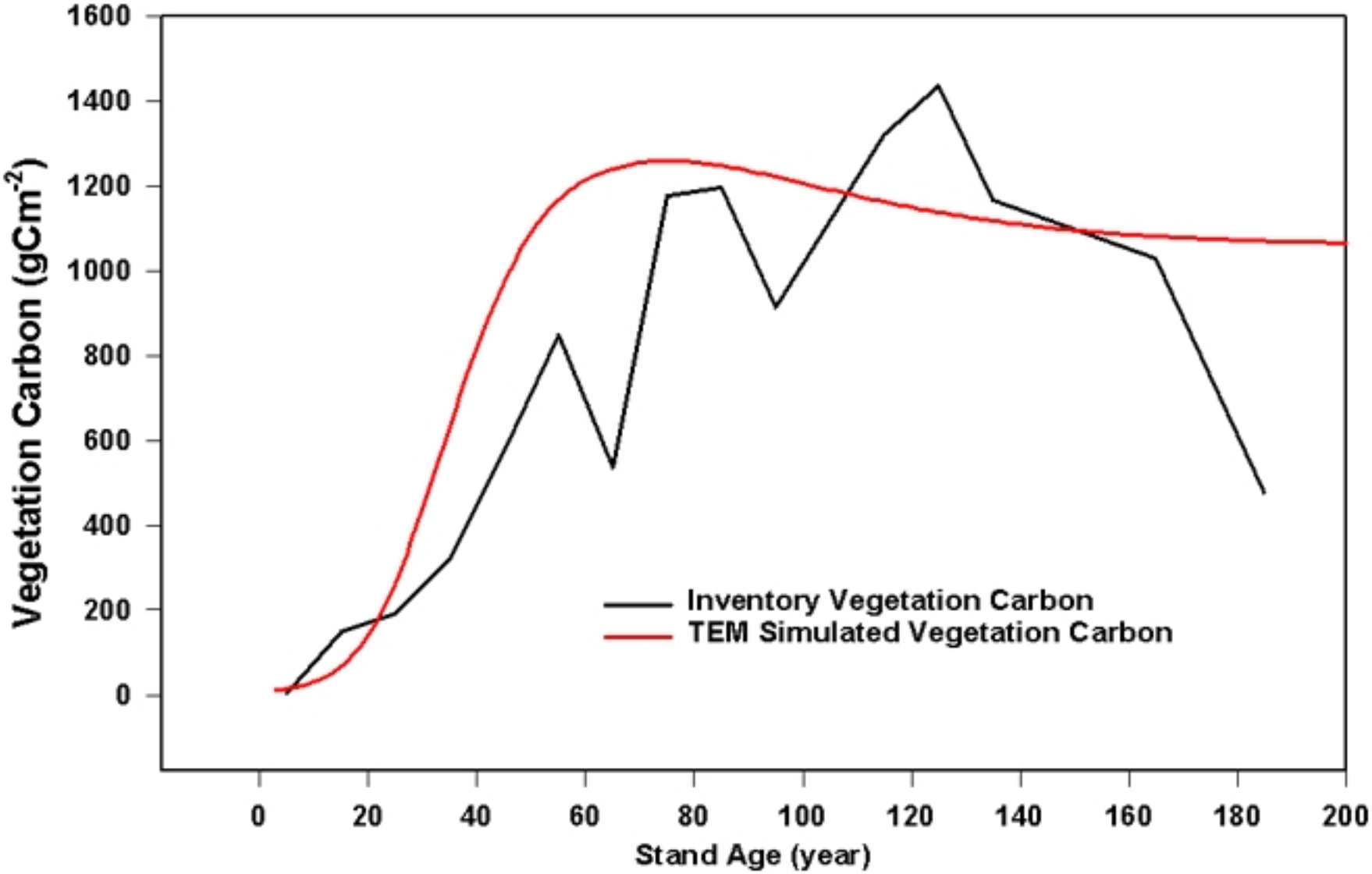

Soil Carbon vs. Stand age
Soil Carbon (gCm-2)
14000
12000
10000
8000
6000
4000
2000
0
1800
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
Year
1956 burn
1987 burn
1990 burn
1994 burn
1996 burn
burned 80 years ago
burned 140 years ago
burned 170 years ago


1997 Soil Respiration
Control
Burned
gC m-2month-1
45
40
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
month

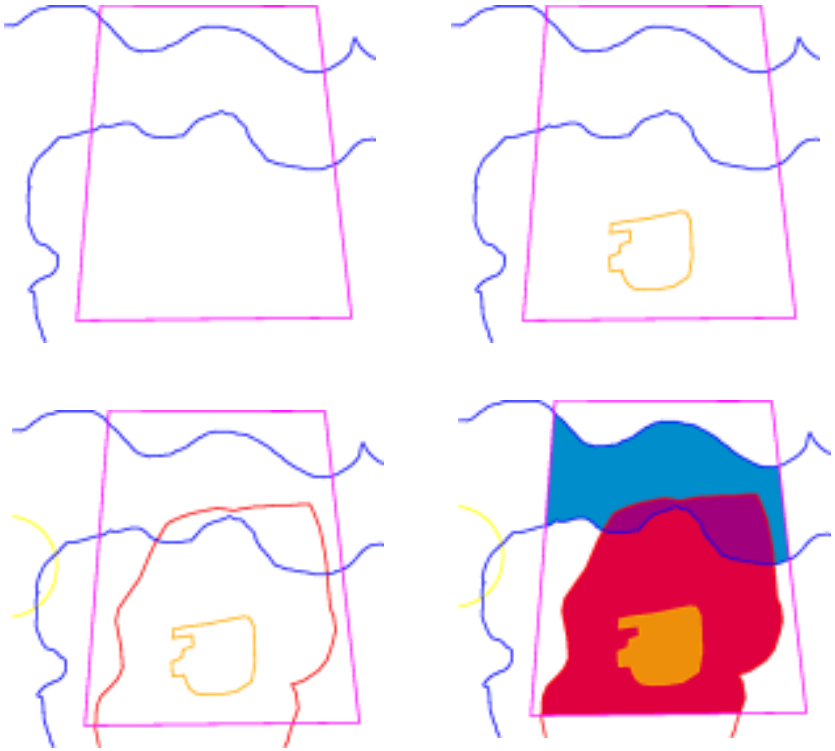

Belowground Carbon vs. Stand age
Soil C (gCm-2)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
20
40
60
80
100
120
140
160
180
Year

Aboveground Vegetation Carbon:

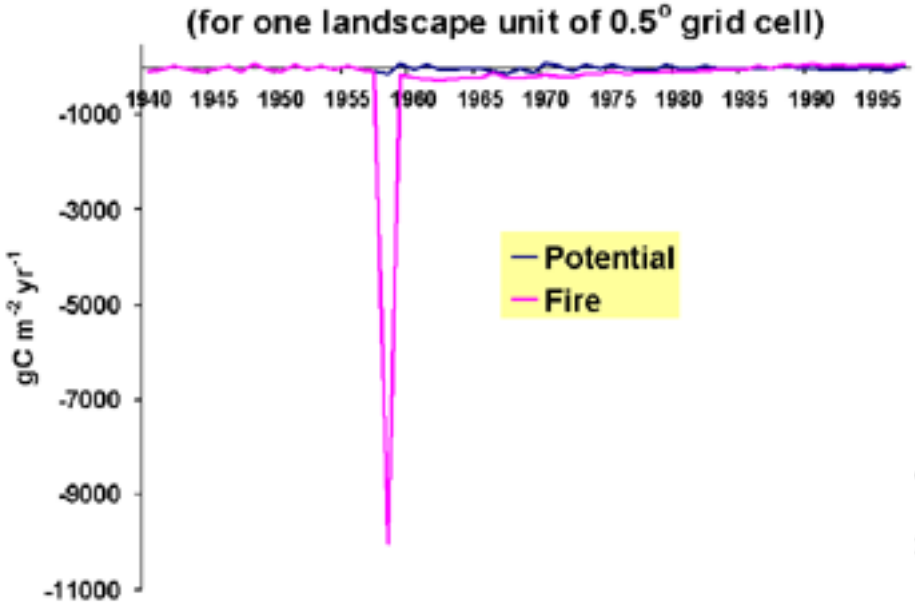
TEM Simulation vs. Inventory Data for Black Spruce Forests in Alaska

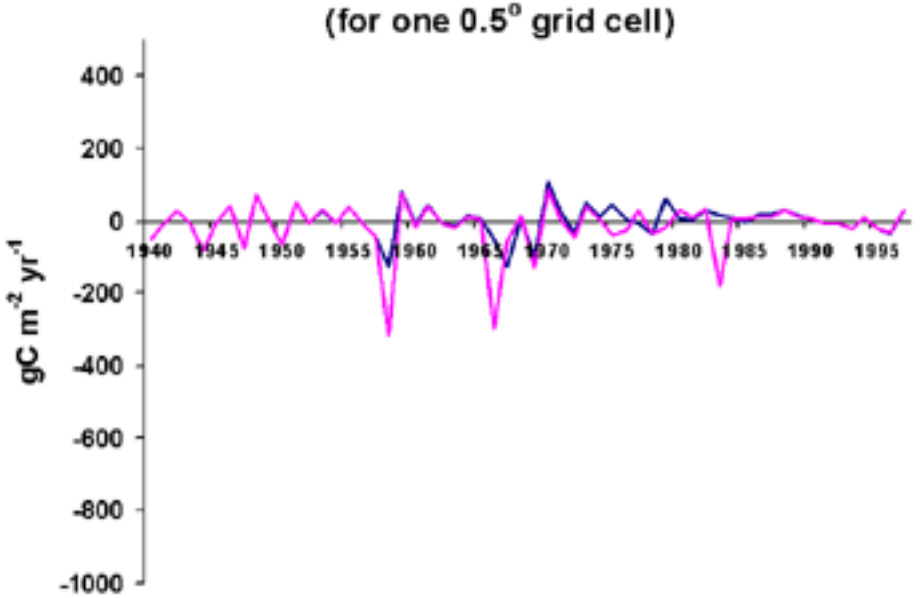


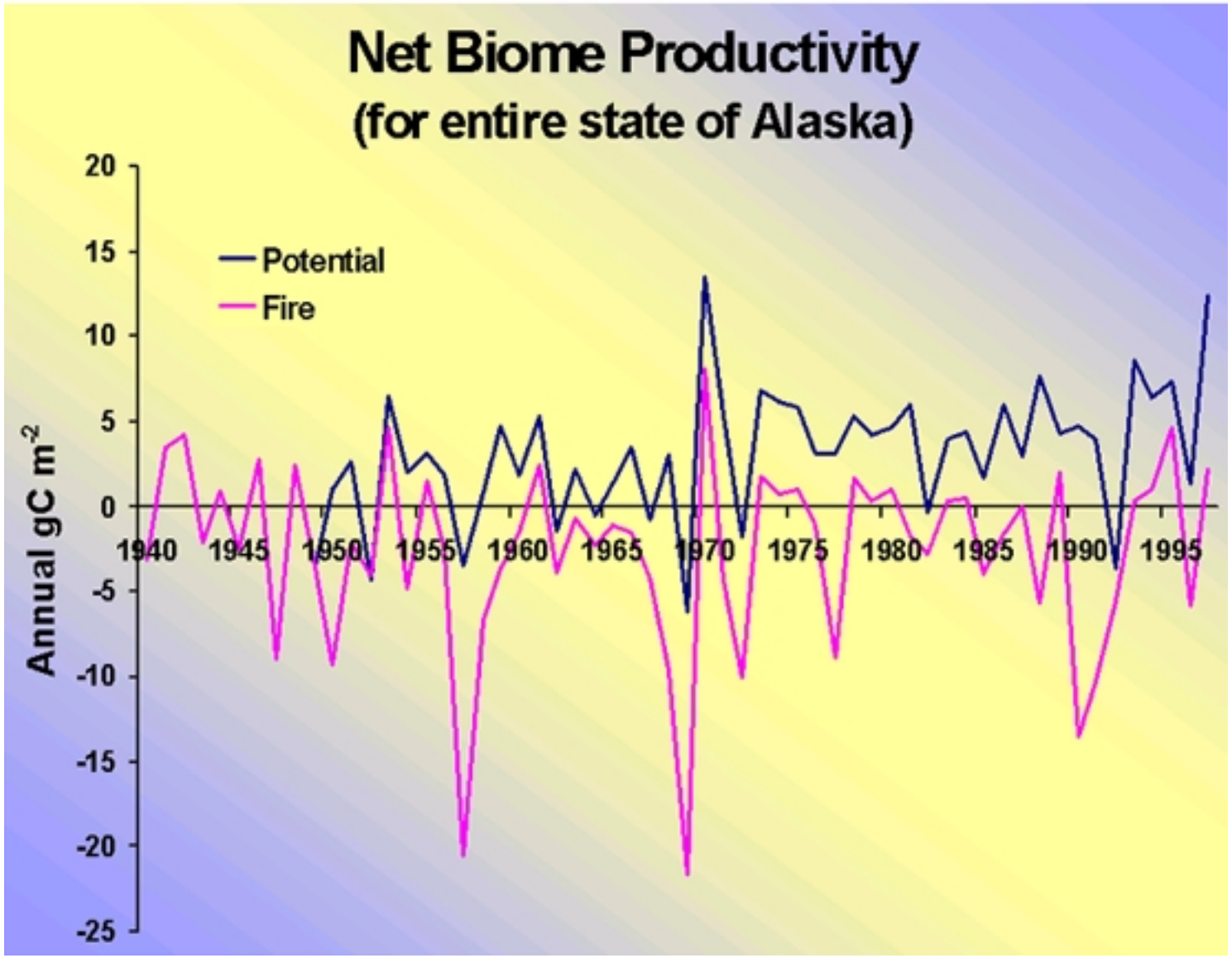
Firescars and Cohorts



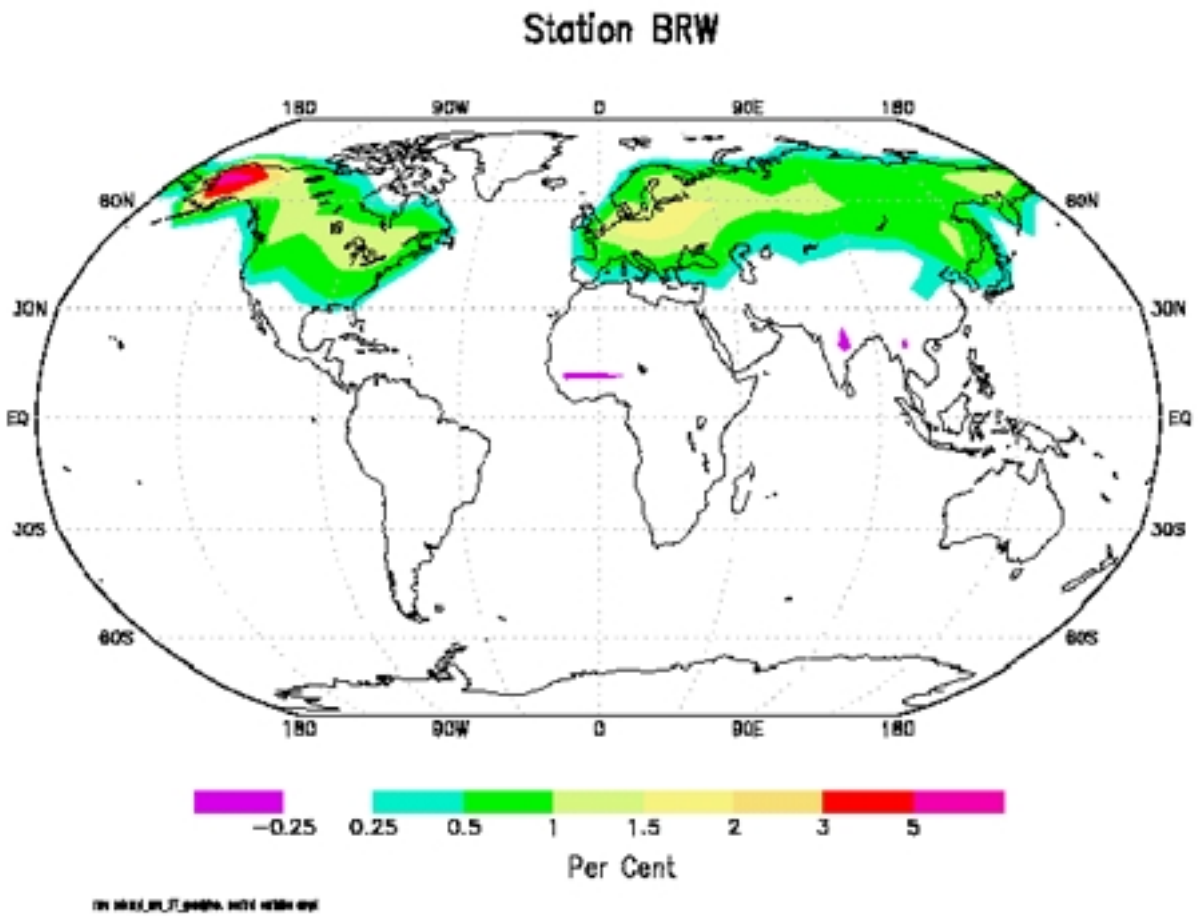
Net Biome Productivity





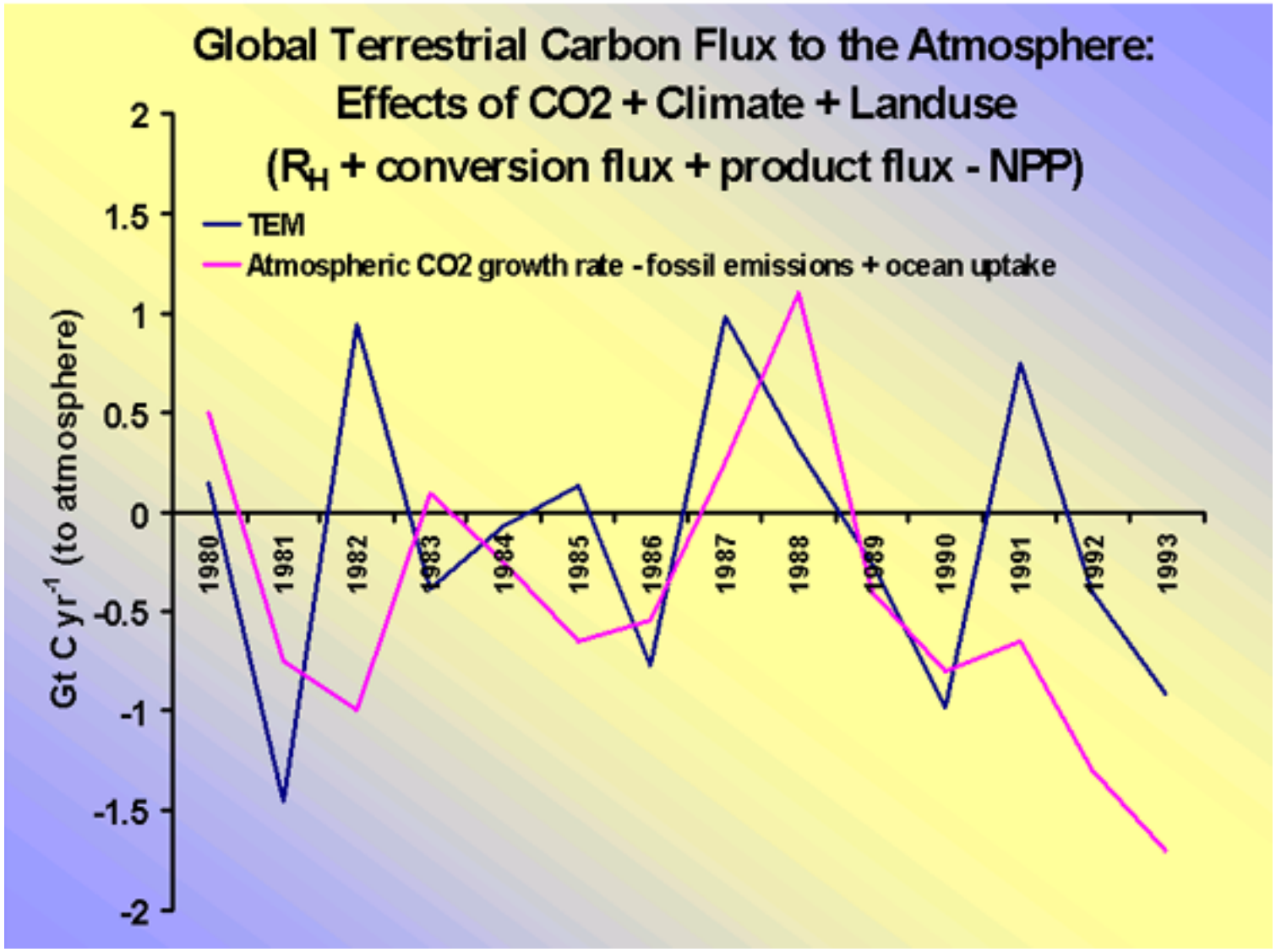

Net Biome Productivity
(for entire state of Alaska)
Potential
Fire
Annual gC m-2
20
15
10
5
0
-5
-10
-15
-20
-25
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995

Simulated Carbon Flux in Alaska: Animation


Station BRW
180
90W
0
90E
180
60N
30N
EQ
30S
60S
−0.25
0.25
0.5
1
1.5
2
3
5
Per Cent

Modeling Historical Responses of Global Terrestrial Ecosystems to changes in Atmospheric Carbon Dioxide, Climate, and Agricultural Land Use

- Changes in atmospheric CO_2 based on Keeling record.
- Historical temperature based on Jones et al. anomalies.
- Historical precipitation based on Hulme et al. anomalies.
- Historical land use based on boolean data sets of (1) Esser and (2) Ramankutty et al.
- Fate of carbon on conversion based on Houghton.


Global Terrestrial Carbon Flux to the Atmosphere:
Effects of CO2 + Climate + Landuse
(R_H + conversion flux + product flux - NPP)
TEM
Atmospheric CO2 growth rate - fossil emissions + ocean uptake
Gt C yr-1 (to atmosphere)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993

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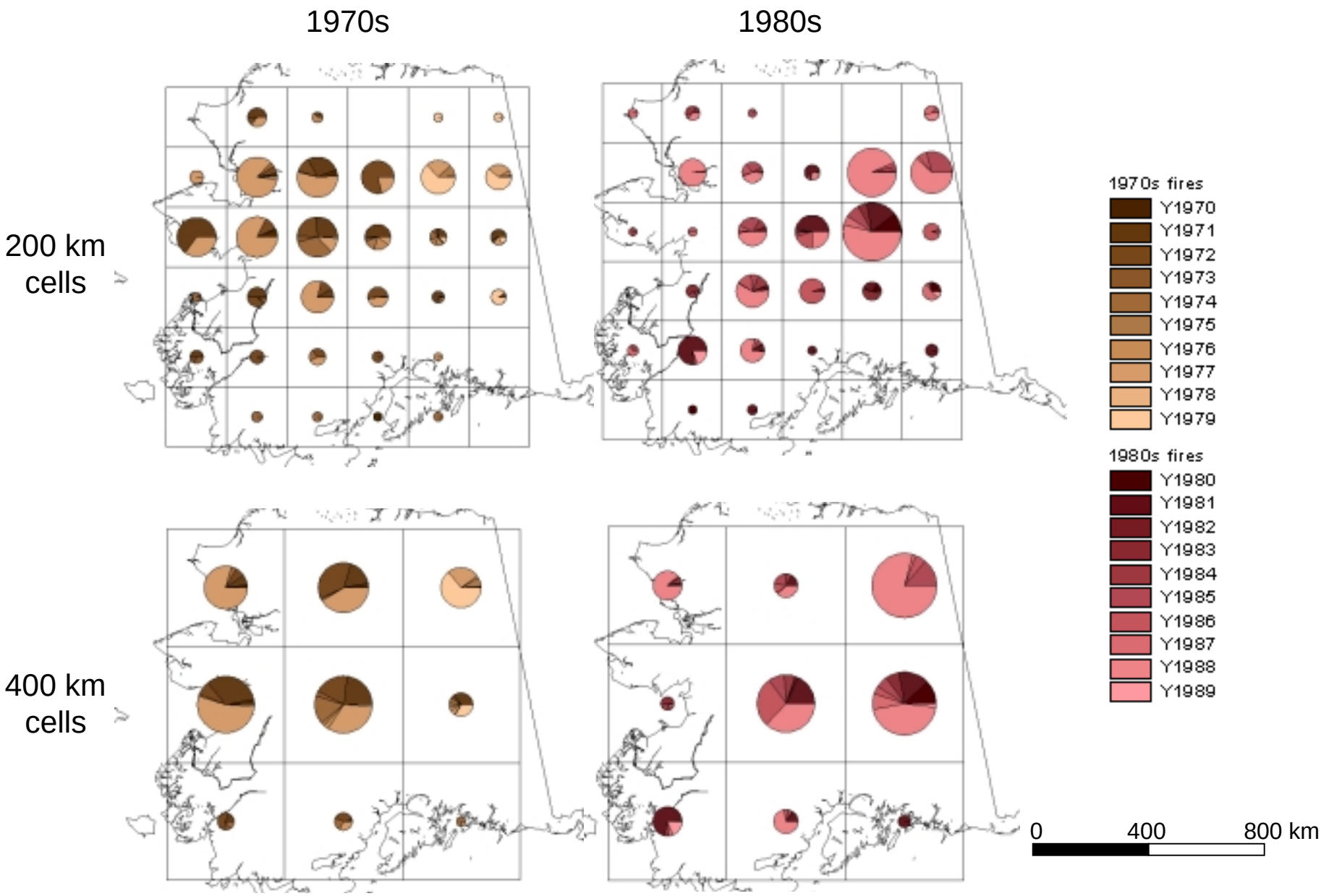
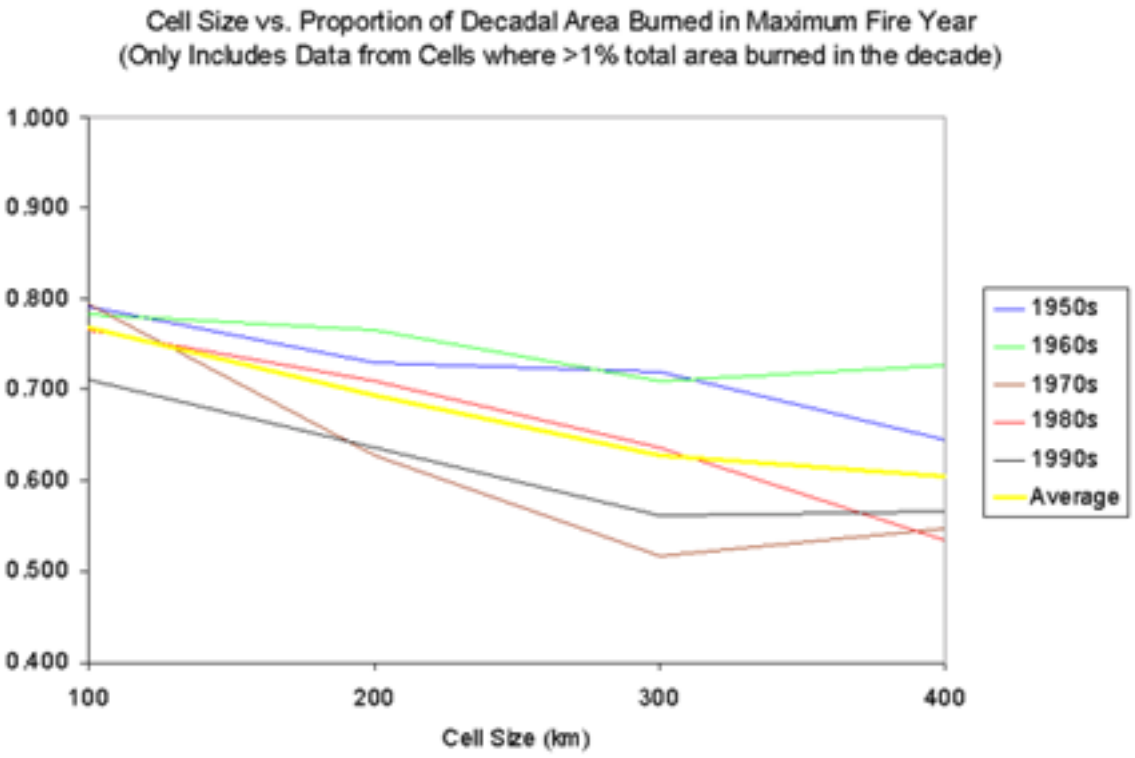
Annual Area Burned as a Proportion of Decadal Area Burned



Annual Area Burned as a Proportion of Decadal Area Burned at Regional Scales in Alaska



- On average, 50-80% of the area burned in a decade is burned in the maximum fire year.
- Within smaller regions, the impact of the largest fires and fire years is greatest.
- Fire regime dominated by very large fires and fire years.

Evaluating the role of interannual climate variation in proportion of area burned at half-degree resolution:

Logistic Regression Model:

$$\text{Proportion Burned} = e^{LP} / (1 + e^{LP}) \text{ where}$$

$$LP = -14.939 + 0.0896T_{MAY} + 0.6478T_{JUNE} - 0.00933\ SNOWPACK_{MAY}$$

- The model overestimates number of cells with small burns and underestimates number of cells with large burns
- Aggregating results to the state scale, the model explains 33.7% of the interannual variance in area burned across Alaska
- Over 47 years, the model predicts area burned within a few km^2

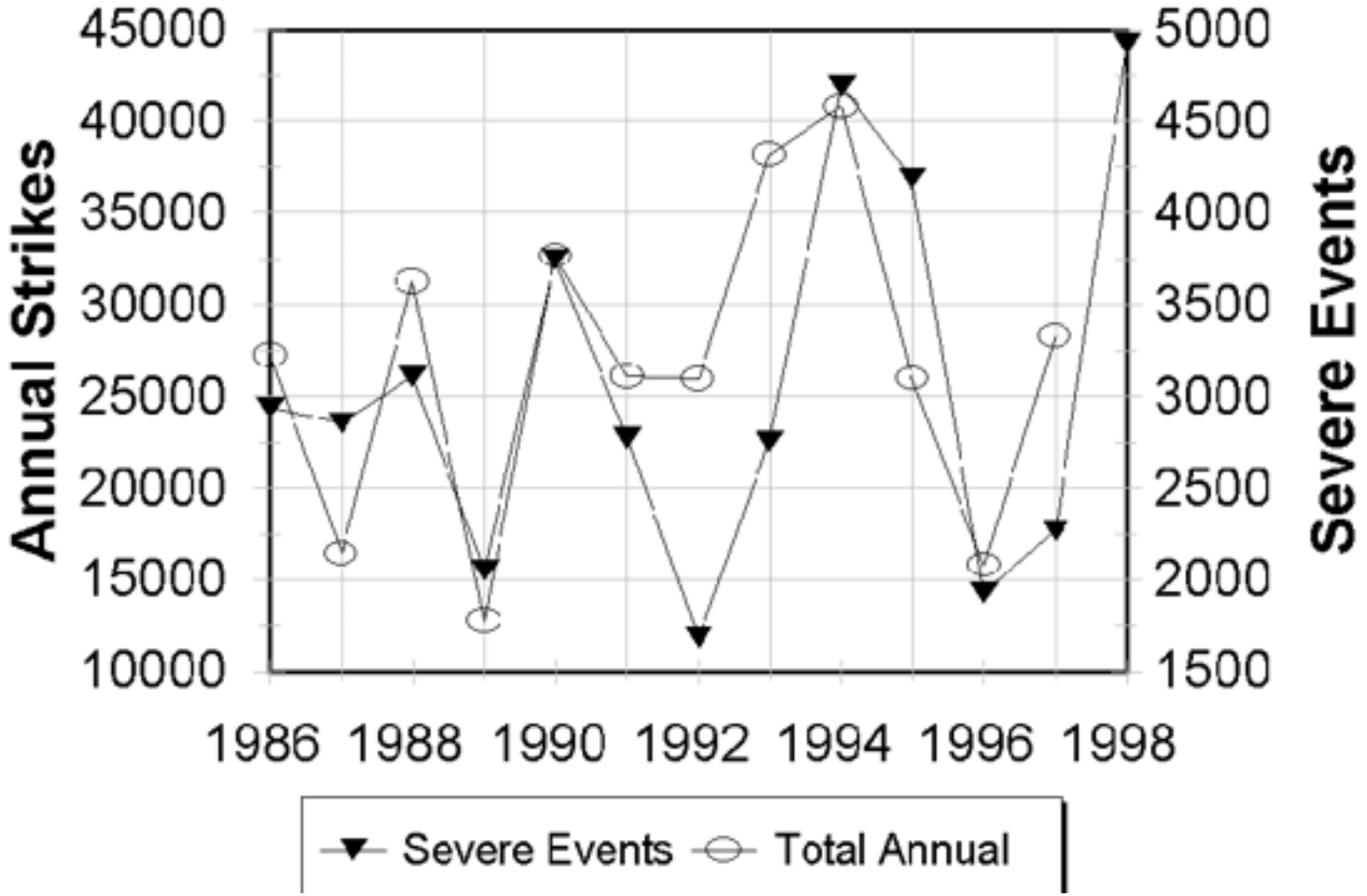
Evaluating the role of fire history:

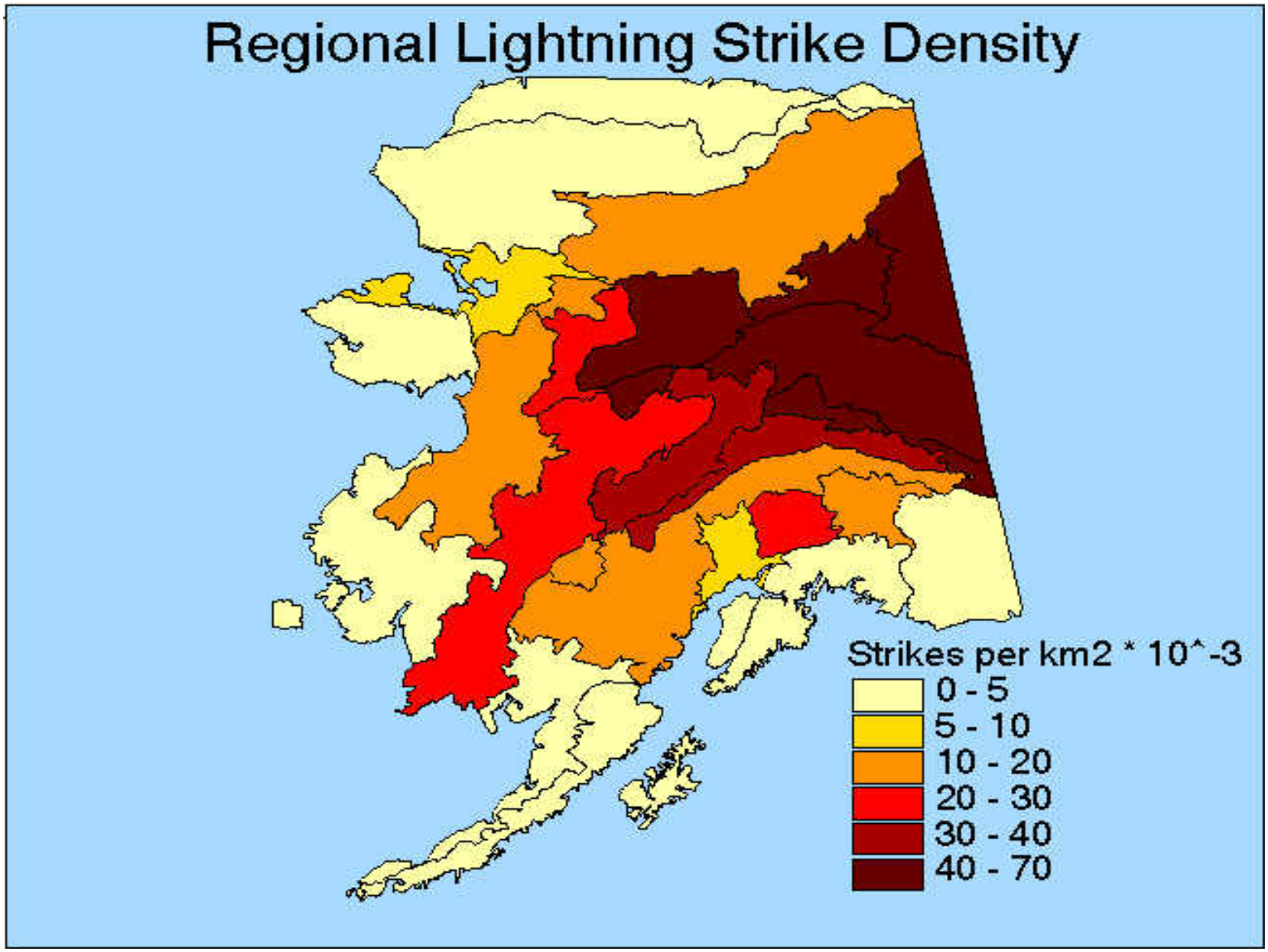
We examined the pattern of burning in fire-history cohorts that existed in 1990:

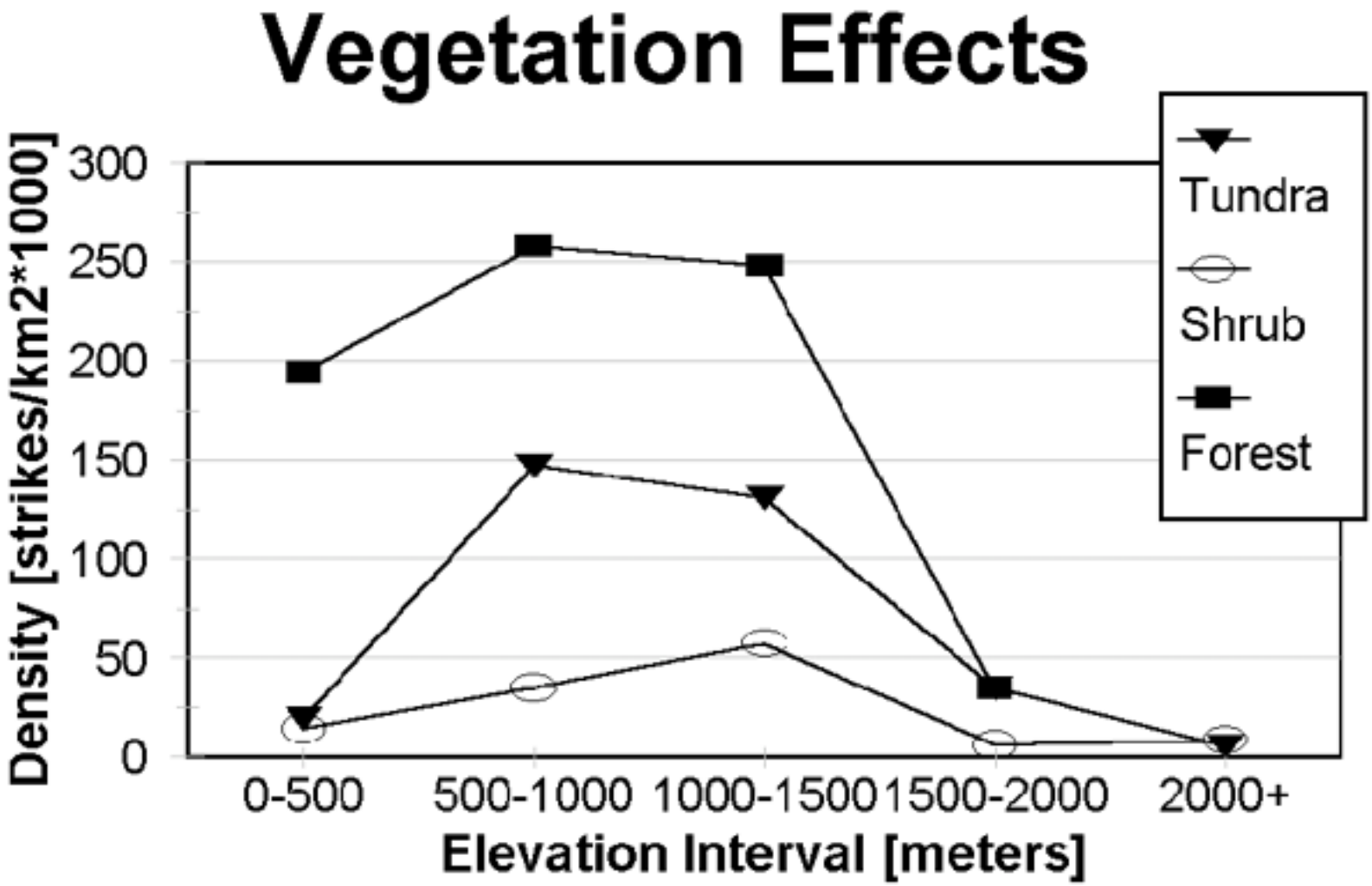
	Burned	Unburned
Previous Burn > 40 years ago	135	1675
Previous Burn <= 40 years ago	54	1115

- **Of 2979 cohorts in 1990, 60.8% had not burned in last 40 years**
- **Of cohorts burned in 1990, 71.4% had not burned in last 40 years**
- **Chi-square Test: P = 0.0025**

Lightning Variation




Regional Lightning Strike Density
Strikes per km2 * 10^-3
0 - 5
5 - 10
10 - 20
20 - 30
30 - 40
40 - 70


Vegetation Effects
Density [strikes/km2*1000]
300
250
200
150
100
50
0
0-500
500-1000
1000-1500
1500-2000
2000+
Elevation Interval [meters]
Tundra
Shrub
Forest

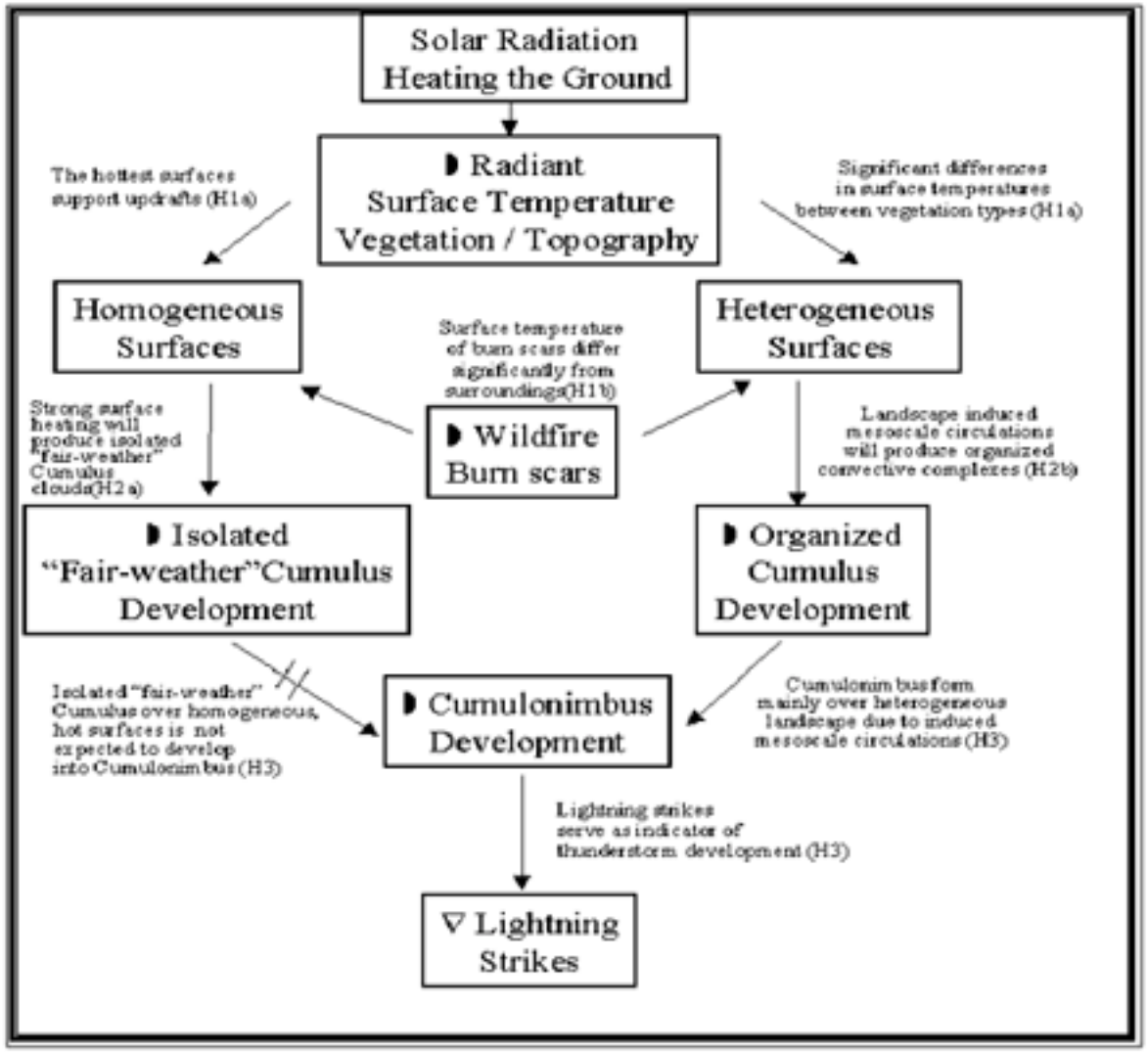


Figure 1: Flow Chart of Tested Hypotheses

Text explains the hypothesis tested. H-numbers refer to hypothesis.

◗ Detectable by remote sensing techniques

▽ BLM / ASF automated network data

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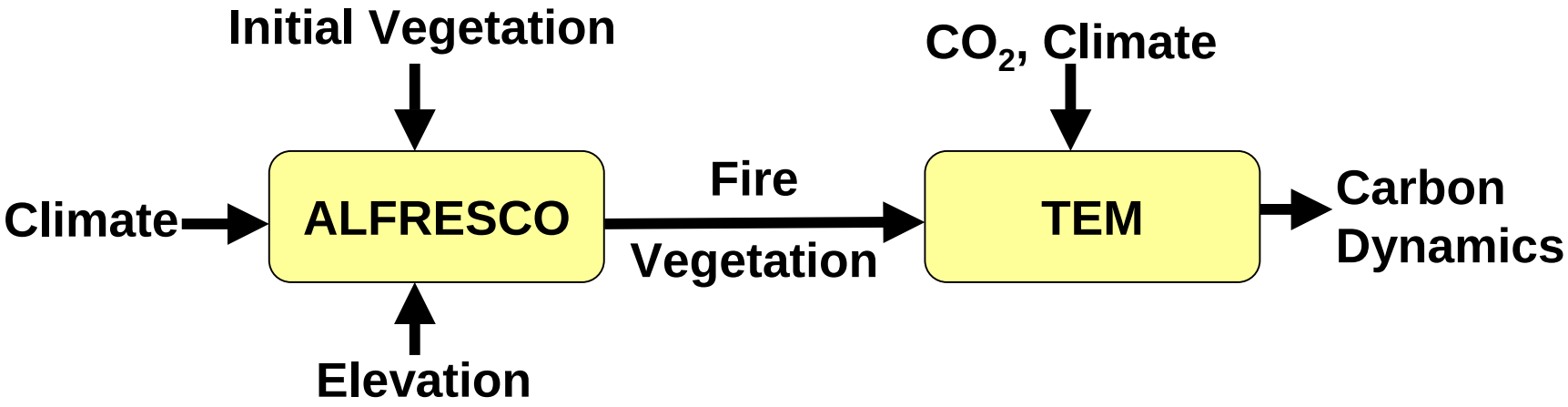
Modeling the influence of climate variability on carbon dynamics through changes in disturbance regime and ecosystem structure and function:

Coupling of ALFRESCO with TEM

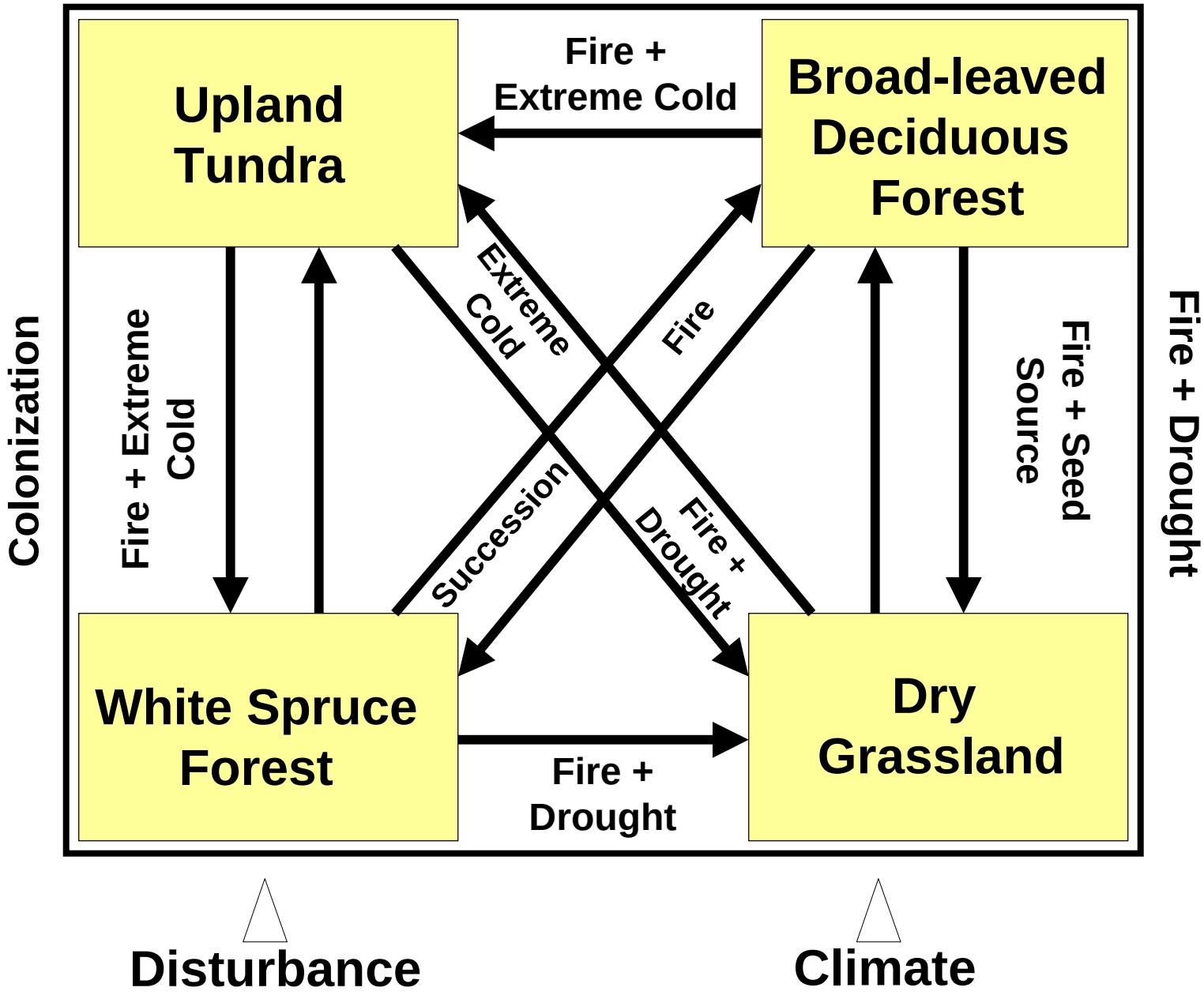


Simulation Specifications:

Spatial Scope: 200 km by 400 km region of the Seward Peninsula

Temporal Scope: 1950 to 2100

Climate Data: Max Planck historical connected with Hadley CM2 projected climate

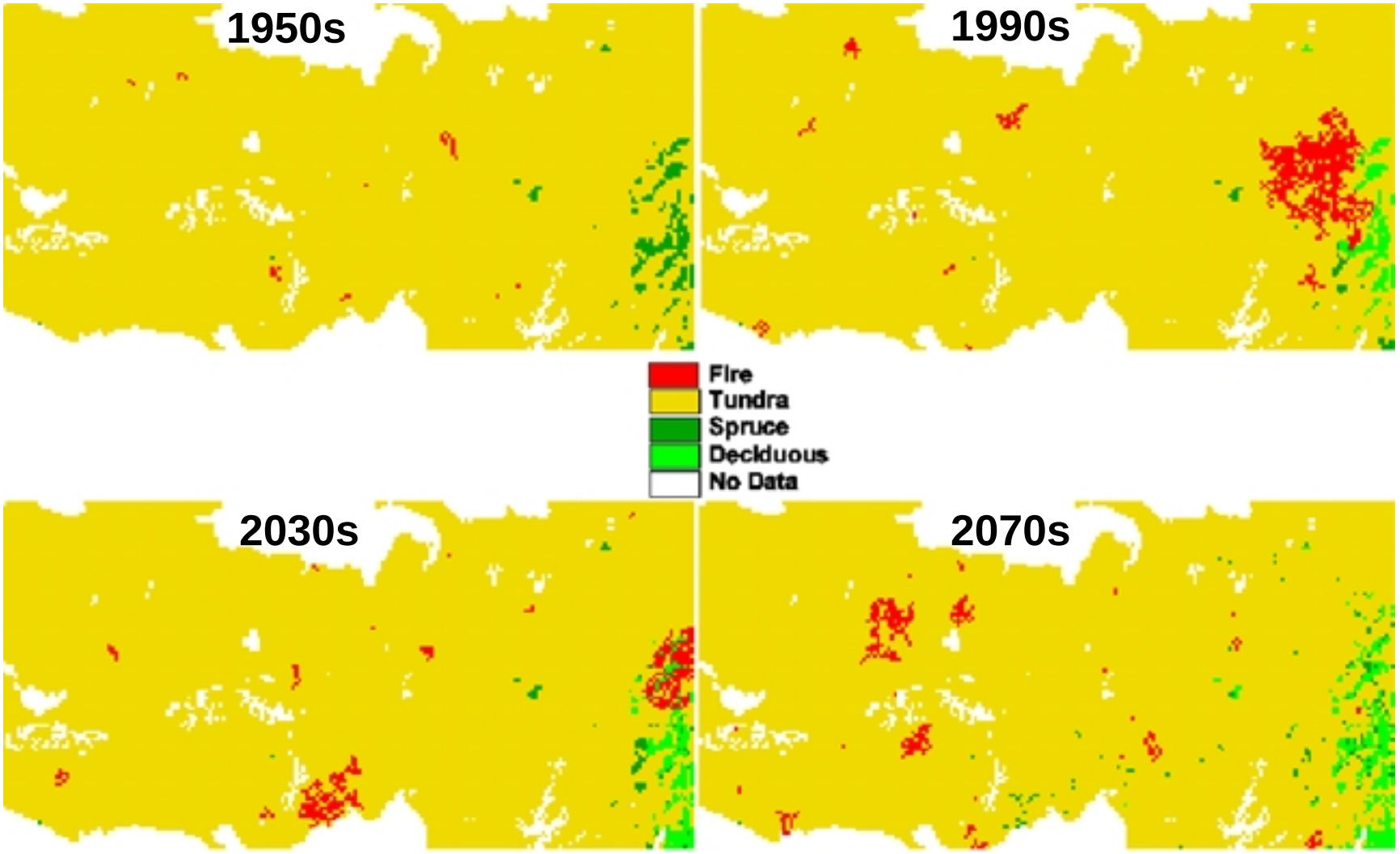

Upland Tundra
Fire + Extreme Cold
Broad-leaved Deciduous Forest
Colonization
Fire + Extreme Cold
Extreme Cold
Fire
Succession
Fire + Drought
Fire + Seed Source
Fire + Drought
White Spruce Forest
Fire + Drought
Dry Grassland
Disturbance
Climate

Fire History of the Seward Peninsula, Alaska Between 1950 and Present:

Number of Fires and Area Burned Per Decade

	Number	Area (km^2)
Observed	10	2212
Simulated by ALFRESCO	10	1552

ALFRESCO Simulated Fire and Vegetation
Seward Peninsula AK



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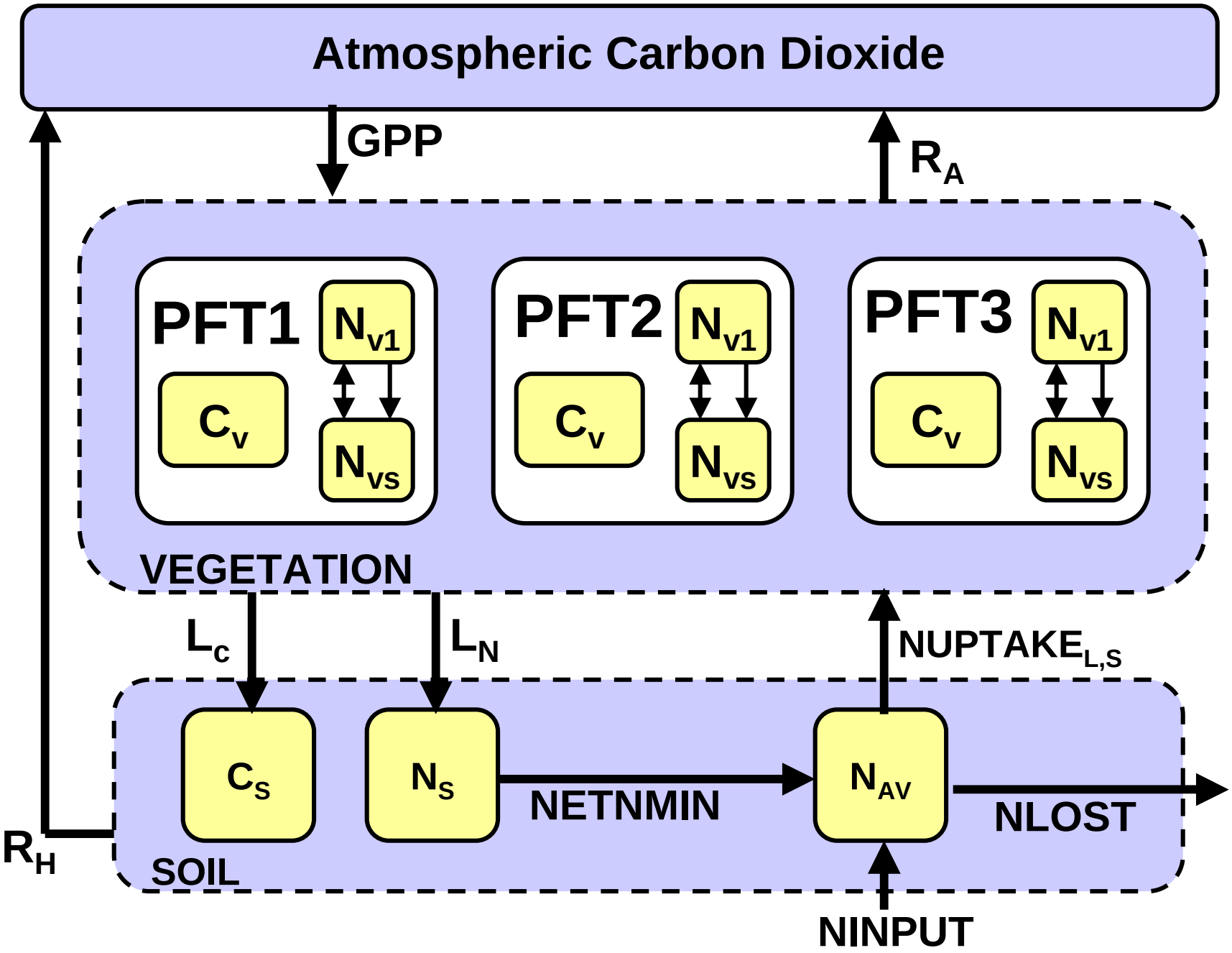
Atmospheric Carbon Dioxide
GPP
R_A
PFT1
N_{v1}
C_v
N_{vs}
PFT2
N_{v1}
C_v
N_{vs}
PFT3
N_{v1}
C_v
N_{vs}
VEGETATION
L_C
L_N
$NUPTAKE_{L,S}$
C_S
N_S
NETNMIN
N_{AV}
NLOST
R_H
SOIL
NINPUT

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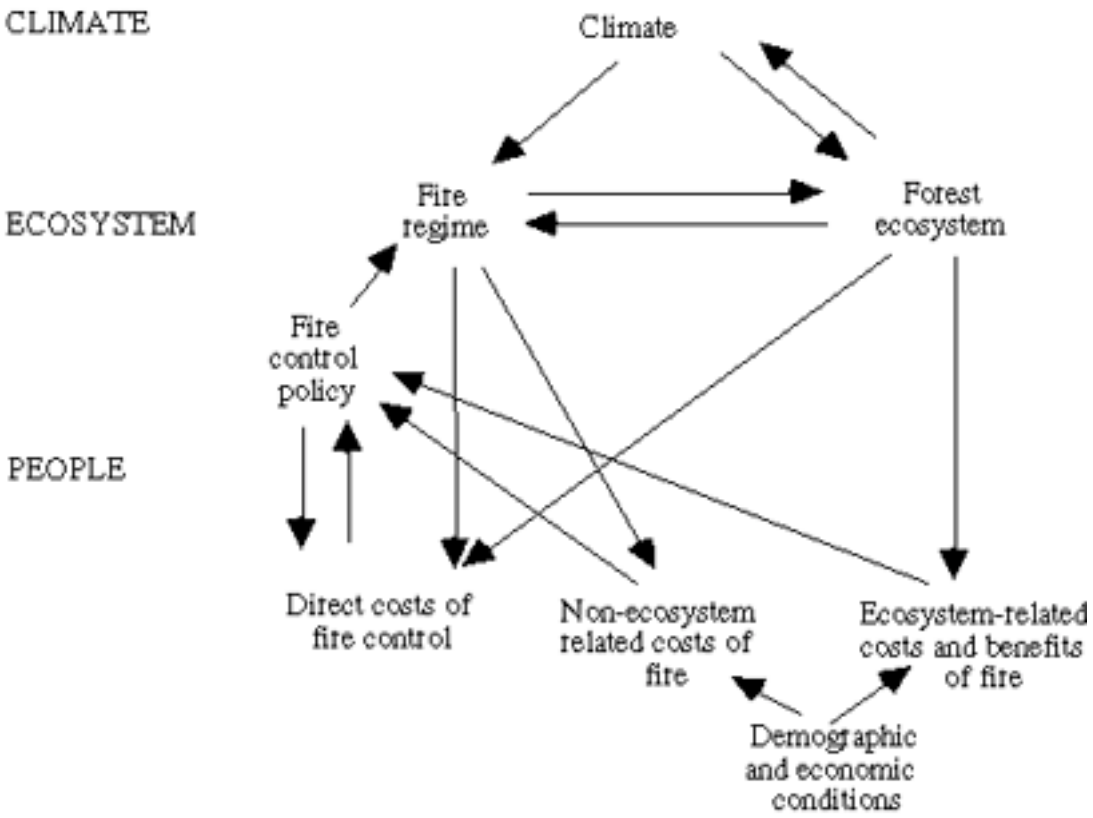

CLIMATE
ECOSYSTEM
PEOPLE
Climate
Fire regime
Forest ecosystem
Fire control policy
Direct costs of fire control
Non-ecosystem related costs of fire
Ecosystem-related costs and benefits of fire
Demographic and economic conditions

Significant Results

- **Theoretical exploration of factors that influence the level of false change detection in estimates of land cover change.**
- **Making progress in developing a methodology to estimate decadal scale land-cover change in high latitude ecosystems.**
- **Progress in modeling effects of climate on permafrost dynamics, ecosystem function, and aspects of the disturbance regime.**
- **Progress in coupling models of ecosystem structure and function in high latitude ecosystems.**
- **Progress in modeling the role of elevated atmospheric CO_2, climate, and agricultural land use in the global carbon cycle.**

Policy Implications

- **Relevant to international negotiations with respect to controlling the concentrations of radiatively active gases in the atmosphere.**
- **Providing support for the use of spatially explicit and temporally explicit vegetation, disturbance, and climate data in the Alaska Regional Assessment.**
- **Conducting pathfinding research for the application to Alaska of the models in the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP), which is an important component of the National Assessment.**
- **Regional and global analyses will contribute to the IPCC assessment process.**

Manuscripts in Preparation
(Expect submission by end of project)

- **Verbyla et al. Potential bias in land cover change estimates associated with positional errors**
- **Macander et al. Vegetation dynamics after fire in interior Alaska.**
- **Zhuang et al. Modeling permafrost dynamics and carbon storage in fire-disturbed ecosystems of Alaska.**
- **McGuire et al. The role of fire disturbance, climate, and atmospheric carbon dioxide in the response of historical carbon dynamics in Alaska from 1950 to 1997: A process-based analysis with the Terrestrial Ecosystem Model.**
- **McGuire et al. The role of rising atmospheric carbon dioxide, climatic variation, and agricultural land use in terrestrial carbon storage: A forward modeling comparison among four terrestrial biosphere models.**
- **Macander/McGuire et al. An analysis of the temporal and spatial dynamics of fire across Alaska between 1950 and 1997.**

Manuscripts in Preparation, continued...
(Expect submission by end of project)

- **Dissing and Verbyla. Landscape interactions with thunderstorms in interior Alaska.**
- **Rupp et al. Historical and projected patterns of fire disturbance and vegetation dynamics on the Seward Peninsula, Alaska.**
- **McGuire et al. Historical and projected patterns of carbon storage on the Seward Peninsula, Alaska: The role of changes in atmospheric carbon dioxide, climate, simulated fire, and simulated vegetation dynamics.**
- **Rupp TS, Starfield AM, Chapin III FS (Submitted) A frame-based spatially explicit model of subarctic vegetation response to climatic change: comparison with a point model. Landscape Ecology.**
- **Rupp TS, Chapin III FS, Starfield AM (Submitted) Response of subarctic vegetation to transient climatic change on the Seward Peninsula in northwest Alaska. Global Change Biology.**

Next Steps

- **Remote Sensing and Spatial Data Sets**
- **Modeling**
- **Human Dimensions**

Next Steps

Remote Sensing and Spatial Data Sets:

- **Better automation of change-detection methodology**
- **Application of methodology to broader region (Alaska and beyond)**
- **Use of new technologies/data - MODIS, LANDSAT 7**

Next Steps

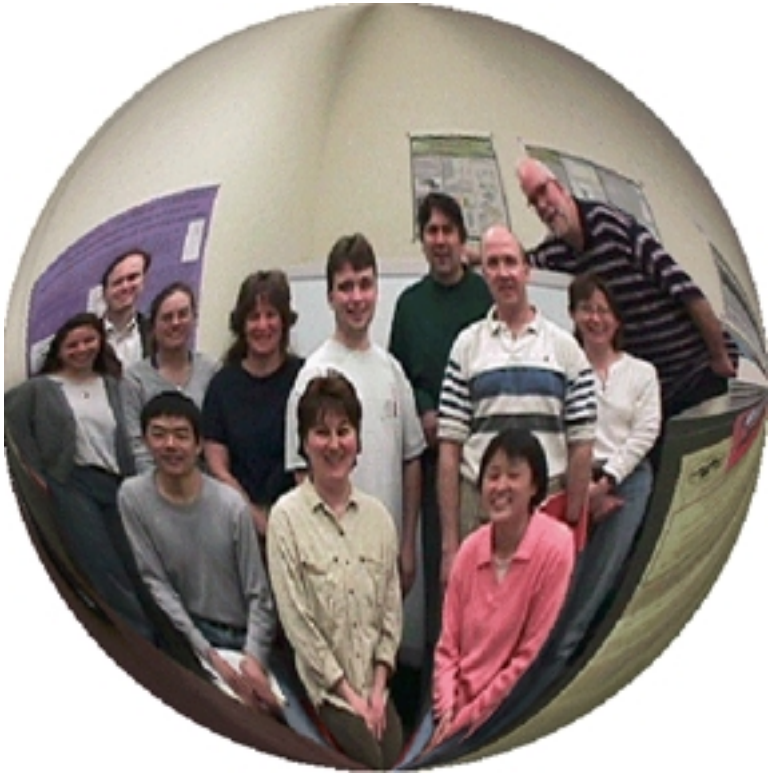
Modeling:

- **Continued development of individual modeling components**
- **Focused effort on a predictive model of the fire regime**
- **Vegetation dynamics based on both population processes and biogeochemistry**
- **Comparison between forward and inverse modeling approaches**
- **Incorporation of human dimensions**

Next Steps

Human Dimensions:

- **Fire control policy**
- **Direct costs of fire control**
- **Non-ecosystem related costs of fire**
- **Ecosystem-related costs and benefits of fire**
- **Demographic and economic conditions**



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http//alces.sel.uaf.edu